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Effects of Radioactive Contamination and Human Disturbance on the Mammals of Fukushima, Japan

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by

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Dedication

For my family, thank you for all of your love, support, food, coffee, and help with laundry. This is the only page you really need to read.

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Abstract

The Fukushima Daiichi Nuclear Power Station accident is one of two disasters ranked as a Level 7 on the International Nuclear Event Scale, the highest possible rank. The Fukushima Prefecture and surrounding region, including the people and wildlife, were contaminated with large amounts of radioactive material. It is well known that ionizing radiation causes many negative effects on the health of animals. This study used motion activated cameras throughout the Fukushima Daiichi Exclusion Zone and surrounding area to investigate the effect of chronic exposure to low-dose radiation on medium- to large-sized mammal abundance and distribution. Only mild effects of ambient radiation were found. Instead, human disturbance associated with clean-up operations along the outside of the exclusion zone significantly affected mammal distribution and abundance.

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Introduction

The disaster at the Fukushima Daiichi Nuclear Power Station (F1-NPS) on March 11, 2011 resulted in the release of huge amounts (~20 PBq of Cesium-137) of radioactivity into the surrounding areas (Kato et al. 2018). The Fukushima Prefecture and adjacent region were blanketed in radioactive contamination. Radioactive particles released into the atmosphere resulted in both wet and dry deposition across the landscape. The International Atomic Energy Agency (IAEA) classified the F1-NPS accident as a Level 7 on the International Nuclear Event Scale, the highest possible rating on the International Nuclear Event Scale (Saito et al. 2018). Only one other event was given this rating, the Chernobyl NPS accident (Table 1.1). Whether the effect of radiation within the Fukushima Daiichi Exclusion Zone is negligible or significantly affecting wildlife populations within the zone is still highly debated (e.g. Møller and Mousseau 2006, Strand et al. 2017).

Following the F1-NPS accident the government ordered evacuations and established an exclusion zone which closed the most highly contaminated areas off from the public (Figure 1.1). Human disturbance is now extremely limited inside the exclusion zone and animals have naturally migrated into the area. The impacts of human disturbance related to the clean-up and remediation activities surrounding the permanent exclusion zone are of potentially greater relevance than the radioactive contamination itself. The government of Japan made decontamination of areas surrounding the exclusion zone a high priority with projected costs to exceed $1T in the coming decades. The main goal of the remediation efforts was to lower external radiation dose rates to potential inhabitants to under 5 mGy/year and to promote habitation of these marginal areas. Between 2011 and 2016 these areas were evacuated while extensive efforts were made to “clean” the buildings and roadside areas of contaminated soil. Peak remediation periods began in 2014 ending by 2017 (IRSN 2016). Massive remediation efforts occurred just outside of the permanent exclusion zone involving hundreds of thousands of men and associated construction equipment.

Despite the catastrophic nature of NPS accidents, relatively few scientists have been able to acquire funding and permits in order to work toward overall conclusions of the ecological effects of these disasters. Additionally, there is a lack of funding for radioactive contamination sites and the effects of radiation are difficult to detect. With a global push toward nuclear power, similar accidents are inevitable. Despite the challenges, extensive research on the effects of such contamination in the areas surrounding NPS accident sites is essential for the safety of both wildlife and humans. The UN Chernobyl Form (2006) suggested that the effects of radiation were small in comparison to human disturbance; however, there have been several studies published since 2006 that found significant effects of radiation (reviewed in Møller and Mousseau

2006 and Strand et al. 2017). One objective of the study reported here was to assess the impact of this disturbance on mammal distribution and abundance outside and near the periphery of the permanent exclusion zone.

Occupancy

Studies of spatial distribution of mammals in the Chernobyl Exclusion Zone have concluded that because mammals inhabit the zone and occupy areas contaminated by radiation the animals are not negatively affected by radiation (e.g. Webster et al. 2016). Webster et al. (2016) suggested that because common species (e.g. *Canis lupus*, *Vulpes vulpes*) are equally detectable across their study sites those populations are not affected by radiation. However, when using camera traps specifically targeting medium- to large-sized mammals minimal survey effort is required to capture such common species.

Several studies have shown that the contaminated area is occupied by wildlife; however, it is necessary to acknowledge the difference between occupancy and negative effects of radiation and human disturbance. The contaminated area simply being occupied by wildlife does not guarantee there are no or negligible negative effects of contaminants and the area is supporting healthy populations and a thriving community. Animals naturally migrate into available habitat, so it is not surprising these species occupy the exclusion zone. Occupancy cannot be used as a reliable evaluation of the effects of radiation. It is necessary to compare the number of individuals across the radiation gradient in order to reliably determine if radiation is affecting the wildlife.

Variation

The results of empirical studies on the effects of radiation on wildlife are often conflicting. The difficulty of determining the effects of radiation stems from the large degree of variation in the distribution of radionuclides, variation in effects among species and among individuals of the same species, limitations in sampling design (e.g. sample size), and even variation caused by weather and seasons (Galván et al. 2014, Møller and Mousseau 2016). Variation in the effects of radiation among species and individuals of the same species may result from a number of aspects including, but not limited to: diet, habitat choice, home range size, individual behavior, antioxidant levels, amount of unavoidable stress (e.g. migration distance), and ability to manage damage (e.g. DNA repair mechanisms, reallocating antioxidants). The heterogeneous distribution of radionuclides themselves creates a highly variable gradient across the landscape. This variation makes the home range size of each species important because that will determine the difference in radiation levels the individual experiences. Additionally, the radionuclide distribution is constantly changing due to phenomena such as wildfires. One example of a redistribution of radioactive particles involves the uptake of contaminated nutrients by trees throughout the growing season. These contaminated nutrients are then incorporated into leaves which then fall to the ground creating a fresh, hot layer. Such phenomena create seasonal differences in contamination levels further complicating the exposure and dose individuals receive. For example, Nemoto et al. (2018) analyzed ^{137}Cs content in *Ursus thibetanus* (Asian black bear) and *Sus scrofa* (wild boar) in Fukushima and found that ^{137}Cs varied both between seasons and between the two species. This variation makes it difficult to generate conclusions regarding the general effects of radiation.

Individual Level Effects

Despite confusion among the field, there have been several individual level studies focusing on the effects of radiation exposure on wildlife (e.g. Giraudeau et al. 2018, Mousseau and Møller 2014, Okano et al. 2016, Uematsu et al. 2014). Exposure to radiation causes increased mutation rates (Møller and Mousseau 2015), lower reproductive success (e.g. malformed sperm, Mousseau and Møller 2014), negative effects on brain size and function (mental retardation in prenatally exposed humans, Otake and Schull 1998; brain size in birds, Mousseau and Møller 2014), increases in tumors (Mousseau and Møller 2014), cataracts (in humans, Otake and Schull 1991; in birds, Mousseau and Møller 2014; in rodents, Lehmann *et al.* 2016), albinism resulting from decreased antioxidant levels (Mousseau and Møller 2014), and asymmetry (Møller 2002) (reviewed in Mousseau and Møller 2016). Møller and Mousseau (2015) completed a meta-analysis on studies of mutation rates across taxa in Chernobyl and found that the effect sizes were overwhelmingly positive, suggesting that mutation rates are significantly elevated as a result of radiation exposure. Abnormalities that are otherwise extremely rare were found to be common in high radiation areas. For example, tumors are extremely rare in unaffected *Hirundo rustica* (barn swallow) populations; however, following the Chernobyl NPS accident there was an unprecedented increase in the number of birds with visible tumors (Møller et al. 2013).

In both *Myodes glareolus* (bank voles) and birds in Chernobyl, sperm quality is reduced (e.g. smaller, reduced swimming ability) in high radiation areas (*M. glareolus*, Kivisaari et al., in review; birds, Mousseau and Møller 2016). However, a similar study of sperm quality done on *Apodemus speciosus* (mice) in Fukushima found no effect of radiation on sperm quality (Okano et al. 2016). This conflicting result may be due to low sample size or differences in contamination levels between the two accident sites. However, contamination levels in Fukushima are high enough to cause a reduction in white blood cell and platelet counts in *Macaca fuscata* (macaque) when the individual received a larger internal dose rate (Urushihara et al. 2018).

Scale of Study

Studies on the individual level are able to detect fine scale, physiological effects caused by radiation. For negative effects to be observed at the population level, these physiological effects must cause significant fitness effects across the population. Increased radiation exposure was associated with higher frequencies of cataracts in *M. glareolus* in Chernobyl (Lehmann et al. 2016). In the same study, more severe cataracts were associated with significantly smaller litter sizes, a fitness cost that could affect the abundance of the population. In order to observe a significant effect on population size resulting from physiological effects of radiation exposure the fitness costs must be severe enough to affect the entire population. A similar study on *M. glareolus* in the Chernobyl exclusion zone found minimal chromosomal rearrangements and enlarged spleens; but, did not find any effect on abundance (Baker et al. 1996). Baker et al. (1996)

strongly notes that although population densities are high, the effects of radiation may be overcome with the increase in population size following the evacuation of 135,000 people from the area. Although population level effects were not found in this species, Baker et al. (2017) found strong evidence for genetic damage to *M. glareolus* living in the most highly radioactive regions of Chernobyl following 50 generations of exposure.

Population level effects may not be discernable from simple abundance studies if migration is overwhelming the negative radiation effects. Møller et al. (2006) described the Chernobyl area as potentially the largest ecological sink described to date when examining bird populations. Using stable isotope analysis of bird feathers from historical (museum) and contemporary samples they concluded that reproduction and survival of birds in the exclusion zone was not sufficient to maintain some populations; therefore, they appear to be maintained by immigration from adjacent uncontaminated areas.

Population Level Effects

Despite complications due to migration, several studies have focused on abundance across taxa in high radiation areas (e.g. Deryabina et al. 2015, Møller and Mousseau 2009, Møller et al. 2015). Estimates of abundance in areas of high radiation compared to low radiation provide valuable insight into population dynamics across the radiation gradient. Again, several studies have found conflicting results regarding abundance in relation to radiation exposure. Deryabina et al. (2015) found no effects of radiation on the abundance of wildlife in Chernobyl. In contrast, reduced abundance in relation to increased radiation levels was demonstrated across taxa (spiders and insects, Møller and Mousseau 2009; birds, Møller, Nishiumi, and Mousseau 2015; mammals, Møller and Mousseau 2012). Comparing within the contaminated areas of Chernobyl, Møller and Mousseau (2009) found significantly decreased abundance of insects and spiders as radiation levels increased. Møller et al. (2015) concluded that at capture sites of higher ambient radiation, Chernobyl birds were less abundant. In fact, the birds became increasingly less abundant over time while radiation levels declined steadily suggesting the effects accumulate over time. Similarly, in Fukushima, birds were found to be less diverse and less abundant in high radiation areas (Møller et al. 2015). Additionally, Møller and Mousseau (2012) found a significant decrease in Chernobyl mammal abundance associated with higher radiation levels.

The combination of various negative physiological-level effects caused by radiation exposure may contribute to lower reproductive success and/or early mortality thus reducing the fitness of that individual. Reproduction is key to sustaining a population and it is well known that radiation exposure negatively affects several stages of reproduction (Strand et al. 2017). Large numbers of individuals that do not survive or successfully reproduce affect the abundance of the population; the degree to which the population is affected depends on the proportion of unhealthy individuals. Abundance is therefore expected to be lower in areas of higher radiation because of the cascading effects of molecular damages to individuals caused by chronic exposure to low-dose radiation resulting in increased adult mortality and decreased reproduction.

Camera Trap Studies

Motion activated camera traps are a quickly developing technology being used to monitor wildlife. These cameras can be placed at remote locations of a study region and left to record animals that pass in front of them with little disturbance to the ecosystem. They are ideal for long-term and large-scale monitoring programs that allow for studies of changes in systems over time and space. Camera traps are used for many different purposes in ecological research including studies of biodiversity (Tobler *et al* 2008), species activity patterns (Yang *et al.* 2018), temporal niches (Massara *et al.* 2018), occupancy (Silva-Rodriguez *et al.* 2018), and density estimations (Nakashima *et al.* 2017).

The identification of individuals is necessary for true density estimates; however, this is not possible for many species of mammals. Marked species (e.g. *Lynx rufus*, *Panthera tigris*) have patterns that are unique to each individual which makes it possible to identify individuals using camera trap images. Unmarked species do not have such patterns. Individuals must be tagged in some way in order to identify individuals of unmarked species; however, tagging is not always practical or necessary. A relative abundance index (RAI) can be calculated without identifying individuals of a species. RAI is the frequency of sightings standardized by the time period of recording and allows the comparison of sightings of a particular species between locations within a population.

We used 71 camera traps over a three year time frame to investigate if there was an effect of chronic exposure to low-dose ionizing radiation on the abundance of medium- to large- mammals in the Fukushima Daiichi Exclusion Zone and surrounding area. The main objective of this study was to determine if a spatial pattern of differences in abundance exists and was correlated with the spatial pattern of higher radiation levels. Additionally, multiple species were used to assess any patterns of lower abundance across taxa within areas of higher radiation (Møller and Mousseau 2006). Doing so is one way to demonstrate an overall effect of radiation given only one accident location (Møller and Mousseau 2006).

Hypotheses

1. Mammals are less abundant and less diverse in areas of higher radiation.
2. Mammals are less abundant in areas of high human disturbance.
3. Mammal abundance will increase over time in the exclusion zone since the accident.

Methods

Sampling

Motion triggered camera traps using IR flash were deployed at a total of 71 sites within the Fukushima Daiichi Exclusion Zone and in the surrounding area (Figure 1.2). The area surveyed was approximately 440 km^2 with cameras spaced a minimum of one kilometer apart, on average. This study uses data from January 2016 to August 2018 and data collection is ongoing. Multiple years of data were used to minimize seasonal variation influencing the results of this study.

Camera sites were selected near roadways or paths for logistical reasons because of the generally mountainous terrain. Specific sites were selected to maximize the probability of detecting animals based on local topography and evidence of animal movements in the vicinity. Cameras were attached to trees approximately one meter above the ground and adjusted so the field of view was ideal for the capture of medium- to large-mammals. When possible, cameras were oriented to face toward the north to minimize direct interference from the sun and to enhance contrast in the images. Vegetation within the field of view was periodically mechanically cleared to reduce false triggering of the motion sensor by wind action. Following each motion trigger the cameras were programmed to take eight images with about a 0.5 second delay between images and a five second delay before the camera can be triggered again. The date, time, and camera number were programmed onto each image.

Cameras were serviced every 3-4 months and were replaced as needed for technological issues. During each servicing event, problematic vegetation was cleared (if necessary), battery status was checked and batteries were replaced (if necessary), and SD cards were replaced with an empty card. Images were later uploaded to a hard drive in the Mousseau Laboratory at the University of South Carolina. Cameras occasionally had to be reprogrammed with the date and time if, for instance, the batteries died, and memory of the settings were lost.

Environmental and Camera Variables

Several environmental and camera variables were quantified for each camera location (Table 1.2). Latitude, longitude, and elevation were recorded for each camera site. On multiple occasions, field measurements for vegetation cover and ambient radiation were taken at each camera location. Radiation levels and vegetation cover estimates were collected multiple times to account for seasonal variation. Vegetation cover was estimated as the percent of cover at the ground, mid-story, and canopy. In addition to field vegetation cover estimates, a normalized difference vegetation index (NDVI) was calculated from satellite imagery to quantify vegetation cover at each camera site (Table 1.2, ArcMap 10.6.1; Environmental Systems Research Institute 2018). The distance was measured from each camera station to highway 114, to the nearest edge of the exclusion zone, and to the closest body of water visible using a satellite imagery base map provided in ArcMap 10.6 (Environmental Systems Research Institute 2018). Camera days per year were calculated as the number of days the camera was deployed and operating properly for each year. Occasionally a camera malfunctioned where the infrared flash did not trigger at night and therefore the cause of the trigger is unknown. To account for such malfunctions the percentage of nights affected by loss of flash were quantified for each camera.

Radioactive contamination across the landscape was highly heterogenous allowing sites to be selected across the entire gradient with minimal change in other, potentially confounding, variables. All camera sites were within or near the edges of forests at elevations ranging from 300 to 1000 m (Table 1.2). Radiation levels were recorded at multiple servicing events as these levels were variable and dependent on environmental factors such as snowfall and time since the disaster (i.e. peak radiation levels dropped as a result of runoff and radioactive decay). Ambient radiation was measured at 1 cm above ground level using a handheld GM tube dosimeter (Model: Inspector, SE International, Inc., Summertown, TN, USA).

Ambient radiation measurements were used as a proxy for exact doses in this study. Garnier-Laplace et al. (2015) reconstructed exact doses for multiple abundance studies which resulted in the same conclusions as the original study using ambient radiation values. Møller et al. (2015) concluded that at capture sites of contaminated areas birds were indeed less abundant. Additionally, birds became increasingly less abundant over time while radiation levels declined steadily suggesting the effects accumulate over time. Dose rates were reconstructed by Garnier-Laplace et al. (2015) which confirmed the original conclusions that bird abundance was negatively affected by radiation levels in the surrounding environment. In Chernobyl, Møller and Mousseau (2013) estimated mammal abundance using tracks in the snow and found a significant decrease in abundance in relation to higher radiation levels. This conclusion was supported by a rigorous dose reconstruction analysis (Beaugelin-Seiller et al., in review). These reconstructions show that ambient radiation values are a sufficient proxy for dose-response analyses such as those conducted here.

Additionally, field radiation values were cross validated using SafeCast, a radiation value map created by measuring radiation along roadways and extrapolating the data across the landscape (SafeCast 2019) for each camera site's GPS position. There was a highly significant positive relationship between the dosimeter and SafeCast radiation measurements ($r = 0.77$, d.f. = 156, $p < 0.0001$) although in most cases the SafeCast measurement underestimated the direct field measurement by a factor of two, on average. This underestimate is likely reflecting the fact that SafeCast measurements are generally taken with a dosimeter mounted on a car door several meters from vegetation where radiation levels are highest.

Data Collection

Following archival in the lab, individual digital images were examined, and any animals observed were recorded along with the date, time, camera number, image number, common name of species, and number of individuals in the field of view. The number of individuals was further broken down into age classes (adult and juvenile). Juveniles were defined as any individuals that were noticeably smaller than adult individuals and/or had color patterns indicating age (e.g. juvenile *S. scrofa* have a striped coat). A third age class of infant was used for *M. fuscata* only to describe individuals holding on to an adult. Records were also made of all human and camera servicing activity as proxies for human disturbance.

A period of one hour was used as the period of record for each animal sighting. If an individual appeared within one hour of the previous sighting of that species, the animals were all included in the same record. The date and time of the first appearance of the individual and the total individuals that appeared within that hour was recorded. Records of number of individuals were made conservatively by counting the minimum number of individuals observed simultaneously. For example, if an animal passed through the field of view from left to right and an animal of the same species passed through in the opposite direction within one hour of the previous observation only one individual was recorded despite the possibility of two individuals being present. Alternatively, if both animals were observed crossing the field of view in the same direction or crossing in opposite directions with more than one hour time difference between the two then two individuals were recorded.

Date Malfunctions

Technological issues caused two types of date malfunctions: incorrect dates and dates that were frozen. Dates were identified as incorrect if the servicing image date did not match the actual servicing date. Sections of images with incorrect dates continued to count days but simply did not start counting on the correct day. For cameras where the date was incorrect, the date was corrected by aligning the image of the camera being serviced with the actual date of servicing recorded in the field notes. The number of days the camera was off was then added to each record following that servicing. Dates that were frozen displayed the exact same date throughout the entire set of images between two servicing events. For these images, time of day was recorded as "day" or "night". Due to the nature of this problem the exact date for the records affected by this malfunction could not be calculated. These records were aligned into years based on the folder they were placed in by their servicing dates. For example, if a section of records came from a folder labeled "May 2017 to July 2017" the records could be confidently placed into the 2017 database. Out of the more than 34,000 records approximately 500 with this problem originated from a folder that contained two years (e.g. November 2017 to February 2018) and were not used in the analysis. This is justified because the records that could not be confidently placed into a year category make up less than 0.02% of the total amount of records.

Validation

The repeatability of the camera models and the student recorders was analyzed to ensure the accuracy of the data and to determine how to reduce error, if possible. Eight undergraduate students assisted with the data collection for this study. To ensure accuracy of the data collection process, all students who recorded data were required to duplicate records for three sets of images. Students were instructed to complete the duplications in the same manner as they completed original records. Each student duplicated one set of images they originally recorded, and two sets of images other students originally recorded where no student duplicated the same student twice. The duplication of records allowed for the comparison of both number of animal observations and correct identification of animals. An intraclass correlation was established for each species using JMP 14, EMP software for both camera and recorder repeatability. The duplicated records were highly correlated for most species (Table 1.3). Nine out of the eleven mammal species recorded had correlations over 0.9 for records duplicated by students. Additionally, during the recording of the main database each student was asked to mark any records they were unsure about for further review and an experienced student would make any necessary corrections. The review further process was not completed for the duplicated records meaning the correlation values are actually an underestimate of the true accuracy of the records. To further improve the accuracy of the main database each record of the two mammal species with correlations lower than 0.9, *Meles anakuma* (badger) and *Procyon lotor* (raccoon), were individually reviewed and corrected if needed.

Nine CuddeBack and 62 Browning cameras were used for this study (Figure 1.3).To determine if different camera models captured the same animals camera pairs were established (Figure 1.4). A pair of cameras consisted of two cameras attached to the same tree pointing in the same direction. Two camera pairs were created within the study site where each pair contained one of each camera model. The correlation between number of sightings of each species for these cameras were highly variable and dependent on species (Table 1.4). *S. scrofa* was the only species that had a correlation higher than 0.9. Low correlations are likely due to differences in camera sensitivity, low sample size given only two pairs, and variation in the field of view.

Statistical Analysis

A relative abundance index (RAI) was calculated by dividing the number of sightings by the camera days for the time period in question. RAI was calculated for each species for the entire study period for each camera. A maximum likelihood generalized linear model with a Poisson distribution was used to analyze the effects of the covariates on the absolute frequencies of RAI for each species [Equation 1] using the statistical software JMP 14, EMP software. A Poisson distribution is typically used for models using count data as the response variable. To eliminate negative values once log transformed, a constant of one was added to each RAI value because RAI values often range from zero to one. The RAI values were then $\log_{10}$ transformed to normalize the data.

Each RAI value was weighed based on the approximate time the camera was in operation. This weight was calculated by first determining the percentage of time the IR flash did not function properly and then using that percentage along with the number of camera days to determine the weight applied to each value [Equation 1]. The weight of the IR flash functioning is dependent on the number of camera days but is not accounted for in the calculation of camera days, so this weighting of RAI values was done to account for the percentage of time the camera did not function properly at night. The continuous covariates were latitude, longitude, elevation, average percentage of vegetation cover at the ground, midstory, canopy, NDVI, average ambient radiation level, distance to highway 114, distance to the closest visible water, and distance to the edge of the exclusion zone. The categorical covariates used were year and if a camera was inside or outside of the exclusion zone.

For species j

RAI_{ij} ~ Poisson (Mean RAI_j)

$E(RAI_{i,j})$ = Mean RAI_j

?(RAI) = (days * 0.5) + (nights * days * 0.5)

$$\log(\text{Predicted RAI}_{i,j}) = \text{Year}_i + \text{Lat}_i + \text{Long}_i + \text{Elevation}_i + \text{Ground\_Average}_i + \text{Midstory\_Average}_i + \text{Canopy\_Average}_i + \text{NDVI\_1}_i + \text{Rad\_Average}_i + \text{Distance\_Highway114}_i + \text{Distance\_Closest\_Water}_i + \text{Distance\_Edge}_i + \text{ExcZone}_i$$

[Equation 1]

Results

Overall, the 71 camera stations recorded for a combined total of 35,845 days during which a total of 96,532 animal observations were made. The animal species observed were: *M. anakuma* (badger), *Chiroptera spp.* (bats), *Aves spp.* (birds), *S. scrofa* (boar), *Felis catus* (cat), *P. lavata* (civet), *Cervus nippon* (deer), *Canis lupus familiaris* (dog), *V. vulpes* (fox), *Lepus brachyurus* (hare), *M. fuscata* (macaque), *Martes melampus* (marten), *Apodemus spp.* (mice), *Phasianus colchicus* (pheasant), *P. lotor* (raccoon), *Nyctereutes procyonoides* (raccoon dog), *Capricornis crispus* (serow), *Sciurus lis* (squirrel), and *Mustela spp.* (weasels) (Figure 1.5). The relative abundance of species which had over 50 sightings throughout the study period (Table 1.5) was analyzed against 13 predictor variables (Table 1.2). Based on number of observations of each species twelve mammal species were chosen for analysis: *M. anakuma, S. scrofa, P. lavata, V. vulpes, L. brachyurus, M. fuscata, M. melampus, P. lotor, N. procyonoides, C. crispus, S. lis*, and *Mustela spp.* (Table 1.5). The environmental and human disturbance variables that were most significantly correlated with relative abundance were highly variable between species (Figure 1.6 – 1.17).

Abundance and Radiation

Average ambient radiation ranged from 0.36 µGy/h to 14.3 µGy/h (Table 1.2). Abundance of eight of the twelve focal mammal species were significantly correlated with average ambient radiation levels where five of those species displayed a positive trend and three of the species displayed a negative trend (Figure 1.18). The relative abundance of *P. lavata, N. procyonoides, M. anakuma, V. vulpes,* and *M. fuscata* increased with increasing ambient radiation whereas the relative abundance of *Mustela spp., L. brachyurus*, and *S. scrofa* decreased (Figure 1.18). The species with the most positive and negative slopes were the *P. lavata* and *Mustela spp*. (Figure 1.18), respectively. Ambient radiation was not the most important predictor for any species (Figure 1.6 – 1.17).

Abundance and Human Disturbance

The distance to highway 114 ranged from 4 meters to 10,570 meters (Table 1.2). Abundance of nine of the twelve focal mammal species were significantly correlated with distance to the highway where seven of those species displayed a negative trend and two displayed a positive trend (Figure 1.19). The relative abundance of *Mustela spp., P. lotor, C. crispus, V. vulpes, L. brachyurus, N. procyonoides, and M. fuscata* increased closer to the highway whereas the relative abundance of *M. anakuma* and *S. scrofa* decreased (Figure 1.19). Distance to the highway was the most important predictor for *V. vulpes, L. brachyurus,* and *P. lotor* (Figure 1.9, 1.10, and 1.14).

The distance from the edge of the exclusion zone ranged from 8 meters to 7,711 meters (Table 1.2). Abundance of nine of the twelve focal mammal species were significantly correlated with distance to the edge of the exclusion zone where seven of those species displayed a negative trend and two displayed a positive trend (Figure 1.20). The relative abundance of *Mustela spp., P. lotor, M. anakuma, P. lavata, C. crispus, V. vulpes*, and *S. scrofa* increased closer to the edge whereas the relative abundance of *S. lis* and *M. fuscata* decreased (Figure 1.20). Distance to the edge not the most important predictor for any species (Figure 1.6 – 1.17).

There were a total of 60 camera stations inside the exclusion zone and 13 outside (Figure 1.2). The abundance of seven of the twelve focal mammal species varied significantly between cameras inside and outside of the exclusion zone where three of those species displayed a negative trend and four displayed a positive trend (Figure 1.21). The relative abundance of *Mustela spp., C. crispus, M. anakuma*, and *S. scrofa* increased inside of the exclusion zone whereas the relative abundance of *S. lis, M. melampus*, and *M. fuscata* decreased (Figure 1.21). Whether a camera was inside or outside of the exclusion zone was not the most important predictor for any species (Figure 1.6 – 1.17).

Relative abundance was significantly correlated with all three human disturbance variables in *M. anakuma, S. scrofa, C. crispus*, and *Mustela spp.* (Figure 1.6, 1.7, 1.15, and 1.17). *V. vulpes* and *P. lotor* abundance were significantly correlated with both the distance to the highway and the edge of the exclusion zone (Figure 1.9 and 1.14). *M. fuscata* and *S. lis* abundance were significantly correlated with both the distance to the edge and whether a camera was inside or outside of the exclusion zone (Figure 1.11 and 1.16).

Abundance and Time

This study included three years: 2016, 2017, and 2018. Eleven of the twelve focal mammal species were significantly affected by year where nine of those species displayed a positive trend whereas two species displayed a weak negative trend (Figure 1.22). The relative abundance of *M. melampus, S. lis, M. anakuma, C. crispus, L. brachyurus, N. procyonoides*, *P. lavata*, *S. scrofa*, and *M. fuscata* increased in abundance over time whereas the relative abundance of *Mustela spp.* and *V. vulpes* decreased over time (Figure 1.22). Year was the most important predictor for *M. melampus* and *Mustela spp.* (Figure 1.12 and 1.17).

Discussion

Overall, responses to human disturbance and several environmental variables were evident in our data whereas radiation effects were much less clear. There was no consistent negative effect of radiation on abundance across the mammal species in this study. Rather, the relative abundance of each species in this study was mostly dependent on the degree to which animals avoid or favor humans, and other environmental factors related to habitat type. Effects of radiation were possibly not found because: 1) by the time of this study, four years after the accident, the level of radioactive contamination had dropped to relatively low levels, 2) acute effects had disappeared while effects stemming from chronic low-dose exposure (if any) had not yet been expressed, 3) the spatial scale used in this study was too coarse to detect any radiation effects, if they existed, 4) confounding effects of human disturbance or environmental factors potentially masked radiation effects, and 5) an insufficient sample size to detect an effect in several species.

Level of Contamination

In Fukushima, the range of dose rates stemming from ambient radiation levels observed during this study was from about 0.5 µGy/hour to 16 µGy/hr. Most of the radiation stems from the decay of ^{137}Cs (half-life of 30.17 years) and, to a much lesser extent, ^{134}Cs (half-life of 2.06 years). For an animal living close to the ground and spending most of its life in the most contaminated forest level this might translate to an annual external dose approaching 100 mGy. Although significant, this is likely to be the highest possible estimate of exposure given that most mammals stand above the ground and move around a territory of varying radiation levels thus reducing the total exposure below such levels. However, this ignores internal doses received via ingestion, which can be substantial and account for a large portion of the total dose, depending on diet. For example, levels of ^{137}Cs and ^{134}Cs in S. scrofa muscle have been reported as high as 7.9 kBq/kg in September 2011 (Steinhauser and Saey 2015). In contrast, in Chernobyl, where many species have shown deleterious impacts of radioactive contaminants (reviewed in Møller and Mousseau 2006), current ambient radiation levels range from 0.5µGy/hour to over 250 µGy/hour (and even higher following forest fires, Mousseau 2017, unpublished data). Body burdens in Chernobyl *S. scrofa* were reported as high as 661 kBq/kg (i.e. about 100 times higher than levels in Fukushima) (Steinhauser and Saey 2015). Thus, the relatively low level of contamination observed in Fukushima and the corresponding dose rates the animals received may not be high enough to cause detectable decreases in mammal populations given the limitations of the present study.

Acute vs. Chronic Exposure

Acute exposure to radiation can result in severe health problems and mortality, depending on the dose received (Otake and Schull 1991). Directly after the Fukushima Daiichi NPS accident the abundance of insects and birds declined significantly (Mousseau and Møller 2014). In Fukushima, *Pseudozizeeria maha* (pale grass blue butterflies) collected in May and September 2011, two and six months following the accident, showed mild morphological abnormalities in May with abnormalities becoming more severe in September (Hiyama et al. 2012). Despite radiation levels declining since the accident, the morphological abnormalities became more severe for several generations. The increase in abnormalities over several generations illustrates the effects of chronic exposure to radiation. *P. maha* collected in 2011 were bred in the lab and both the F1 and F2 generations displayed more severe morphological effects than the field collected individuals despite never being exposed to radiation (Hiyama et al. 2012). This selective breeding study demonstrates that damage caused by radiation remains and is passed down to future generations even when the animals are no longer exposed to radiation.

One effect of exposure to radiation is an increase in the occurrence of mutations (Møller and Mousseau 2015). These mutations are often masked in the wild because it is unlikely two mutations will occur in the same loci. Chronic exposure to radiation increases the probability of mutations occurring in the same loci simply because the mutation rate is higher. The time it takes for these mutations to accumulate, occur at the same loci, and then appear creates a lag period where effects may seem to disappear. The abnormalities in field collected *P. maha* became more severe in the first few generations following the accident possibly because of an accumulation of mutations over time. The lag period created between mutations occurring and showing is longest in mammals whose generation times range from one to six or more years. Several generations are required for the accumulation of mutations to appear and this amount of generations has not occurred for some mammals given this study started only five years following the accident.

The same populations of butterflies were monitored for three years. The percent of morphological abnormalities declined back to normal levels within the three years studied (Hiyama et al. 2015). For butterflies that have several generations per year, a return to normal abnormality rates required approximately 18 generations with the most severe abnormalities occurring around four to six generations. For mammals, the equivalent number of generations certainly has not occurred.

Individual vs. Population Scale

Several studies have found physiological effects examined at the individual level resulting from exposure to radiation including germline mutations (Møller and Mousseau 2015) and increased sperm deformities (Mousseau and Møller 2016). In mammals specifically, white blood cell and platelet counts done on Fukushima *M. fuscata* were inversely correlated with radiation dose (Urushihara et al. 2018). For a population level effect to be observed, physiological effects must be severe enough to cause significant fitness effects across the population. Lehmann et al. (2016) found that cataracts in Chernobyl M. glareolus were associated with smaller litter size. Such connections between physiological damage and fitness effects have not been studied in Fukushima, especially in medium- to large-sized mammals. Additionally, the fitness effects would have to be severe in order to be detected on a population level abundance study. For the previously stated reasons the effects of radioactive contamination on mammals in Fukushima are likely mild, if they exist. Detecting such mild effects statistically in a population level study would require a much larger sample size.

Confounding Effects

If a species was negatively affected by chronic exposure to radiation such that a significant portion of the population was negatively affected, we would expect to see lower abundance in areas of higher radiation. Such a pattern may be disrupted or complicated by human disturbance and environmental factors. Migrating from one area to another decreases abundance in the original location and increases abundance in the new location. For instance, if species actively avoid humans, they will likely venture further into the exclusion zone thereby decreasing their abundance in areas of higher human disturbance and increasing their abundance farther into the zone, where radiation levels are highest. This behavioral change related to human disturbance may mask possible radiation effects caused by negative health effects (e.g. accumulation of mutations). Most of the species studied were significantly influenced by several other factors other than radiation.

Sample Size and Predictors of Relative Abundance

The sample size may not be sufficient to draw reliable conclusions for some species. *S. scrofa* and *M. fuscata* were by far the most abundant animals detected in this study. The remaining species made up less than eight percent of the total sightings for this study.

NDVI and distance to the edge of the exclusion zone were the most important predictors correlated with *S. scrofa* abundance. Increased abundance was associated with increased NDVI values and decreased distance to the edge. *S. scrofa* seem to favor protection from hunting inside the exclusion zone and benefit from ample food availability in the minimally disturbed habitat. Access to farmland outside of the exclusion zone is an additional reason *S. scrofa* may prefer the edge of the exclusion zone over the interior of the zone.

Longitude was the most important predictor variable associated with *M. fuscata* abundance. There were significantly more observations of *M. fuscata* toward the east of our study area. Longitude is significant because it is likely associated with an environmental factor relevant to *M. fuscata* population dynamics that we did not measure. *M. fuscata* group territory size is dependent on available resources in the habitat. Differences in resource availability across our study area may explain the significant correlation between *M. fuscata* abundance and longitude. Future studies could examine the specific habitat types across the longitudinal gradient to determine if habitat is influencing *M. fuscata* abundance.

Overall, environmental factors and human disturbance were better predictors of mammal abundance in the Fukushima Daiichi Exclusion Zone. The abundance of most mammal species in this study was positively correlated with time, as expected. The abundance of the two mammal species that were negatively correlated with time may show such a trend due to insufficient sample sizes for those species. The abundance of each species related to human disturbance variables was highly variable. Some species tended to favor human disturbance whereas some strongly avoided human disturbance. There was no consistent effect of radiation across the species analyzed in this study and the correlations with radiation were often very small. In Chernobyl, where higher levels of radiation have been sustained for a longer time period, decreased abundance of insects (Møller and Mousseau 2009), birds (Møller et al. 2012), and mammals (Møller and Mousseau 2013) was associated with areas of higher radioactivity. Previous research in Fukushima in the first few years following the accident found sharp declines in abundance of birds and insects that were highly correlated with radiation levels (Møller and Mousseau 2009). However, similar trends of decreased mammal abundance associated with increased radiation levels were not supported by this study. Such a trend was possibly not found for several reasons: 1) the level of contamination is not high enough to cause effects in mammals, 2) there has not been a sufficient amount of time since the accident for effects to be observed in mammals, 3) the effects are not severe enough to be observed on the population level, 4) other variables have a much larger effect on the mammals than radiation thereby masking the radiation effects, and/or 5) the sample size in this study was not large enough to detect small effects of radiation. The continuation of mammal surveys in Fukushima over many years will allow researchers to determine if there are indeed no significant effects of radiation exposure, if effects exist but were too small to be detected by this study, or if effects have yet to develop in mammals.

Conclusions

1. Mammals were not consistently less abundant in areas of higher radiation. Human disturbance and environmental factors were more important in predicting relative abundance.
2. Mammals were not consistently less abundant in areas of high human disturbance. Some species avoid humans and some favor human activity.
3. Abundance of all but two species analyzed increased over time.

Tables

Table 1.1 Comparison of three large scale nuclear power plant accidents

	Chernobyl	**Fukushima**	**Three Mile Island**
Date Accident Occurred	April 26, 1986	March 11, 2011	March 28, 1979
Area Significantly Contaminated	~ 200,000 km^2	~ 10,000 km^2	~ 20 km^2
Approximate Amount of Radionuclides Released	5200 PBq	770 PBq	480 PBq
International Nuclear Event Scale Rating	7	7	5

Table 1.2 Justification for and description of each covariate

Variable		Justification	Description	Value Range		
				Minimum	Maximum	Average (SD)
Elevation		Important aspect of habitat because it can influence the plants and wildlife.	Measure of elevation extracted from hand-held GPS unit.	201.16	991.57	492.60 (134.17)
Radiation	Field (Rad_Average)	Quantifies ambient radiation at the exact camera location.	Measured using a handheld dosimeter (Model: inspector, SE International, Inc., Summertown, TN, USA) in microsieverts per hour. Measurements were taken July 2015, July 2016, October 2016, and April 2017 for each camera and averaged.	0.36	14.30	5.68 (3.74)
	SafeCast	Estimate of ambient radiation of the area surrounding the camera location.	Extracted for each camera location in microsieverts per hour from SafeCast Tile Map for the area contaminated by the Fukushima Daiichi accident. https://safecast.org/tilemap/?y=37.899&x=140.419&z=11&l=2&m=2	0.13	13.92	2.84 (2.55)
Vegetation Cover	NDVI	A measure of primary productivity.	Derived in ArcMap 10.6.1 from 2011 Landsat 6 Thematic Mapper imagery Downloaded from https://earthexplorer.usgs.gov/	0.55	0.89	0.81 (0.06)
	Ground	A measure of primary productivity at the ground.	Estimate of the percent of area covered by vegetation in the area directly surrounding the camera. Quantified in July 2016, October 2016, April 2017, and November 2017.	3	100	48 (31)
	Midstory	A measure of primary productivity at the mid-story.		7	80	26 (14)
	Canopy	A measure of primary productivity in the canopy.		20	95	72 (18)
Exclusion Zone	(ExcZone)	Quantifies if a camera location is within the protection of the exclusion or outside of the exclusion zone where human disturbance is frequent, and hunting occurs.	Indicator of if a camera is within or outside of the Fukushima Daiichi Exclusion Zone. 0 = outside, 1 = inside.	0.00	1.00	0.82 (0.39)

Variable		Justification	Description	Value Range		
				Minimum	Maximum	Average (SD)
Distances	Highway 114	Describes the distance to human disturbance.	Measured in ArcMap 10.6.1 in meters of the distance from each camera to the closest point along Highway 114.	4	10570	1883 (2131)
	Visible Water	Describes the distance to large water sources.	Measured in meters of the distance from each camera to the closest body of water visible on the satellite imagery base map in ArcMap 10.6.1	0	1889	330 (409)
	Exclusion Zone Edge (Dist2)	Describes the distance to human disturbance and hunting pressure.	Measured in ArcMap 10.6.1 in meters of the distance from each camera to the closest point along the edge of the Fukushima Daiichi Exclusion Zone.	8	7711	2160 (1571)
Night Camera	Global	Allows for sightings to be standardized by the amount of time a camera was not functioning properly at night (i.e. flash did not occur when the camera was triggered).	Percent of nights a camera was not operating properly for the entire study period and per year.	0.35	1.00	0.96 (0.13)
	2016			0.00	1.00	0.95 (0.17)
	2017			0.00	1.00	0.97 (0.15)
	2018			0.09	1.00	0.95 (0.18)
Camera Days	Global	Allows for sightings to be standardized by the amount of time a camera was functioning.	The number of days a camera was operating properly for the entire study period and per year.	23	1104	574 (334)
	2016			0	366	166 (146)
	2017			0	366	188 (149)
	2018			0	222	130 (96)

Table 1.3 Observer repeatability by species

Species	Repeatability
M. anakuma	0.51
S. scrofa	0.96
P. lavata	0.95
V. vulpes	0.99
L. brachyurus	0.98
M. fuscata	0.94
M. melampus	0.92
P. lotor	0.32
N. procyonoides	0.96
C. crispus	1.00
S. lis	1.00

Table 1.4 Camera repeatability by species

Species	Repeatability
S. scrofa	0.92
M. fuscata	0.72

Table 1.5 Species list

	Total Sightings	Percent of Total
S. scrofa	51,551	53.4
M. fuscata	38,087	39.4
L. brachyurus	2,565	2.7
N. procyonoides	1,759	1.8
V. vulpes	753	0.8
P. lavata	700	0.7
C. crispus	345	0.4
M. anakuma	247	0.3
P. lotor	190	0.2
M. melampus	183	0.2
S. lis	101	0.1
Mustela spp.	51	0.1
Chiroptera spp.	13	0.0
Apodemus spp.	8	0.0
C. nippon	1	0.0

Figures

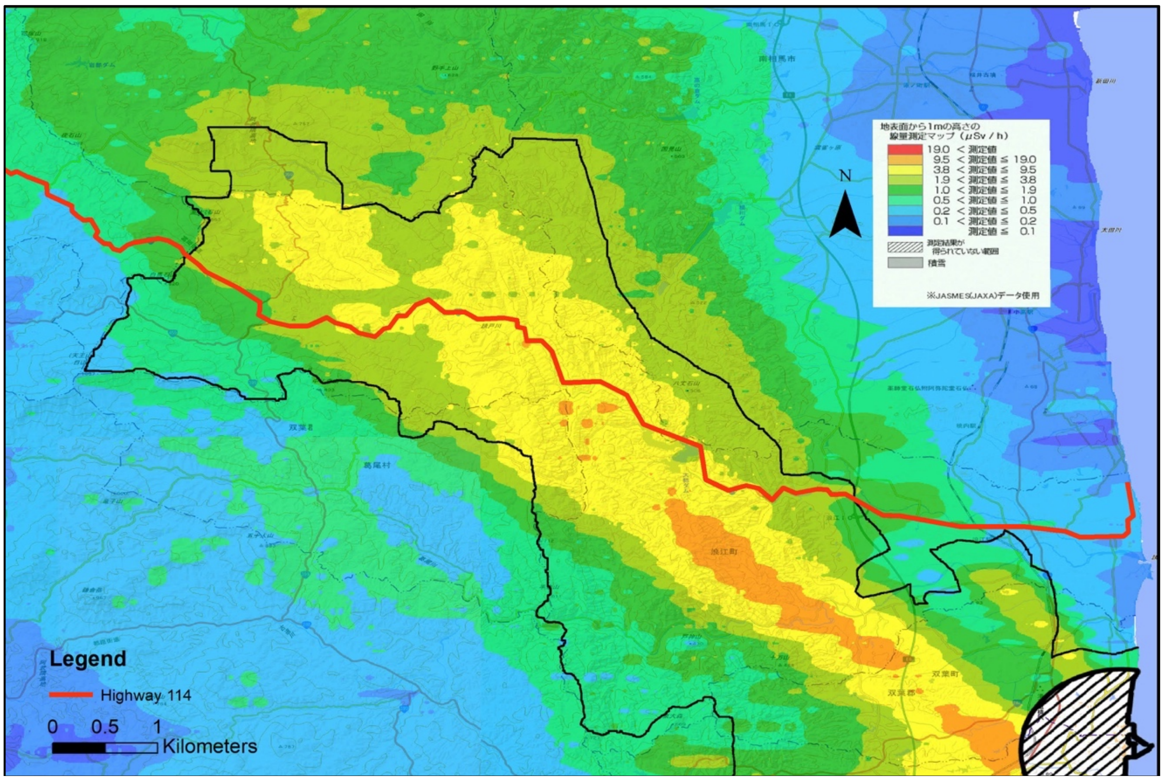


Figure 1.1 Map of the Fukushima Daiichi NPS Exclusion Zone

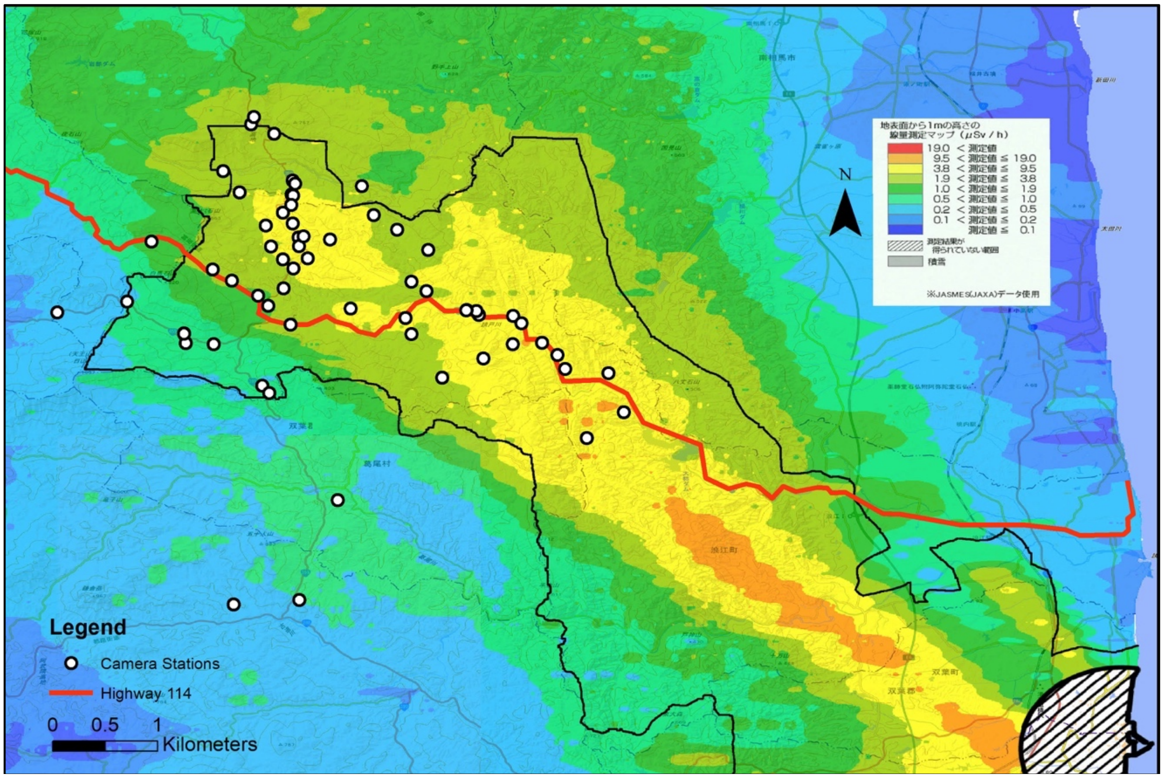


Figure 1.2 Map of camera stations

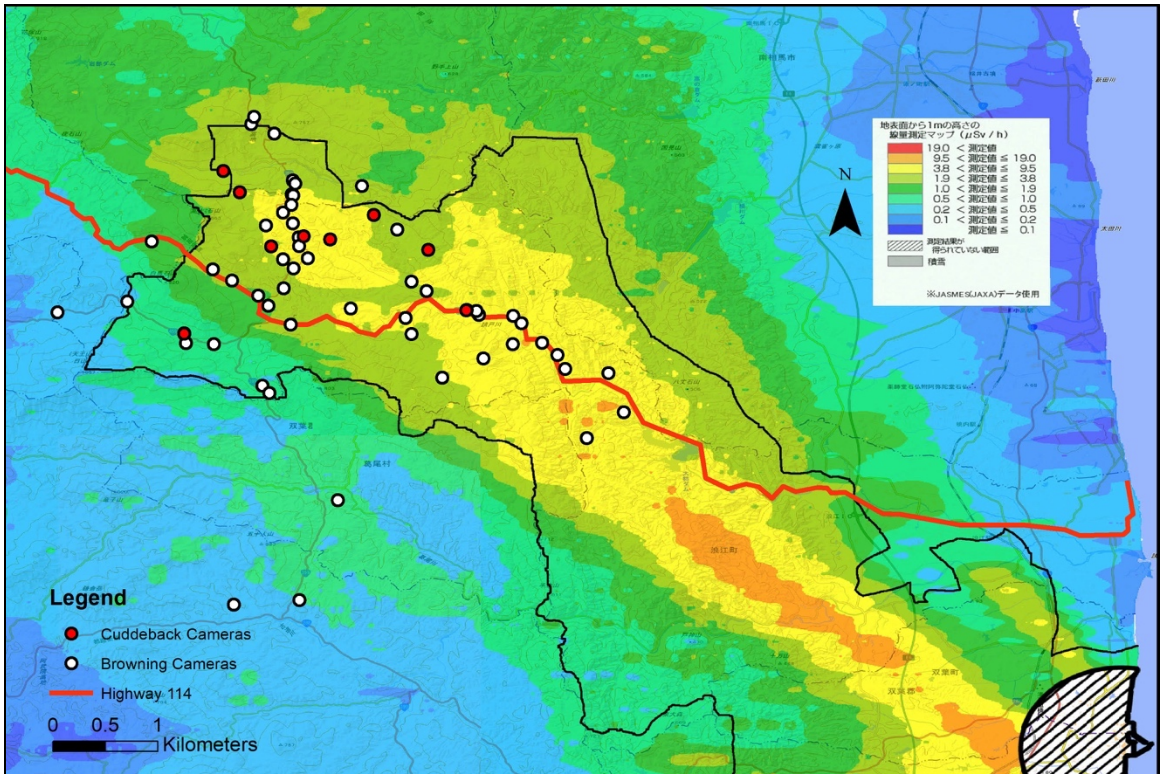


Figure 1.3 Map of camera stations identified by camera model

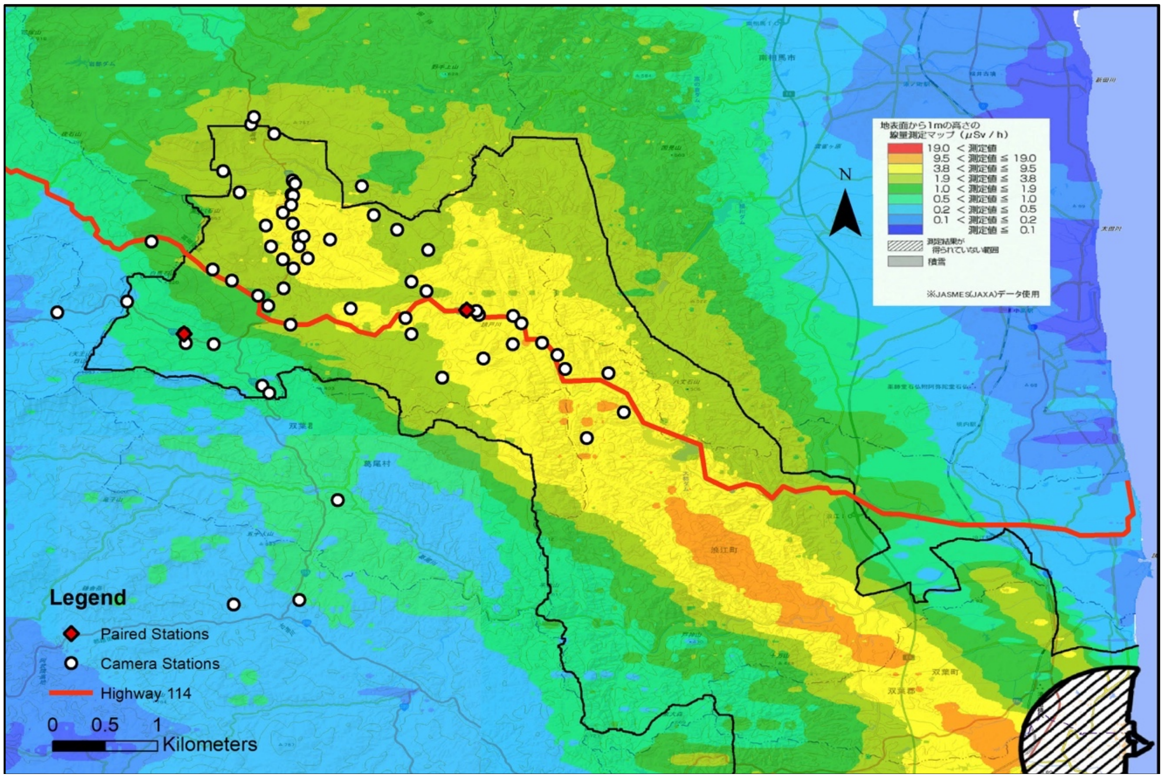


Figure 1.4 Map of camera stations identifying pair locations

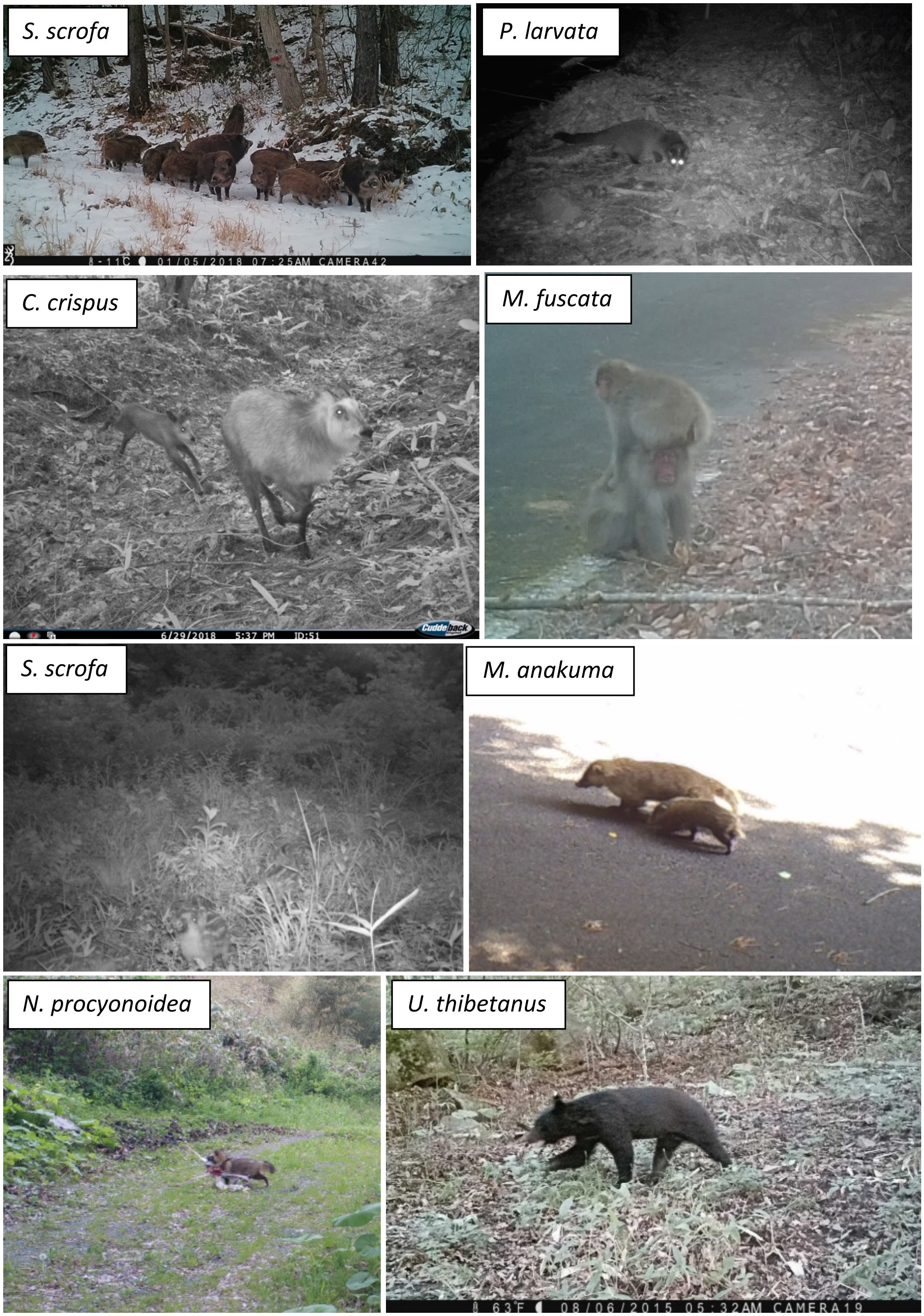
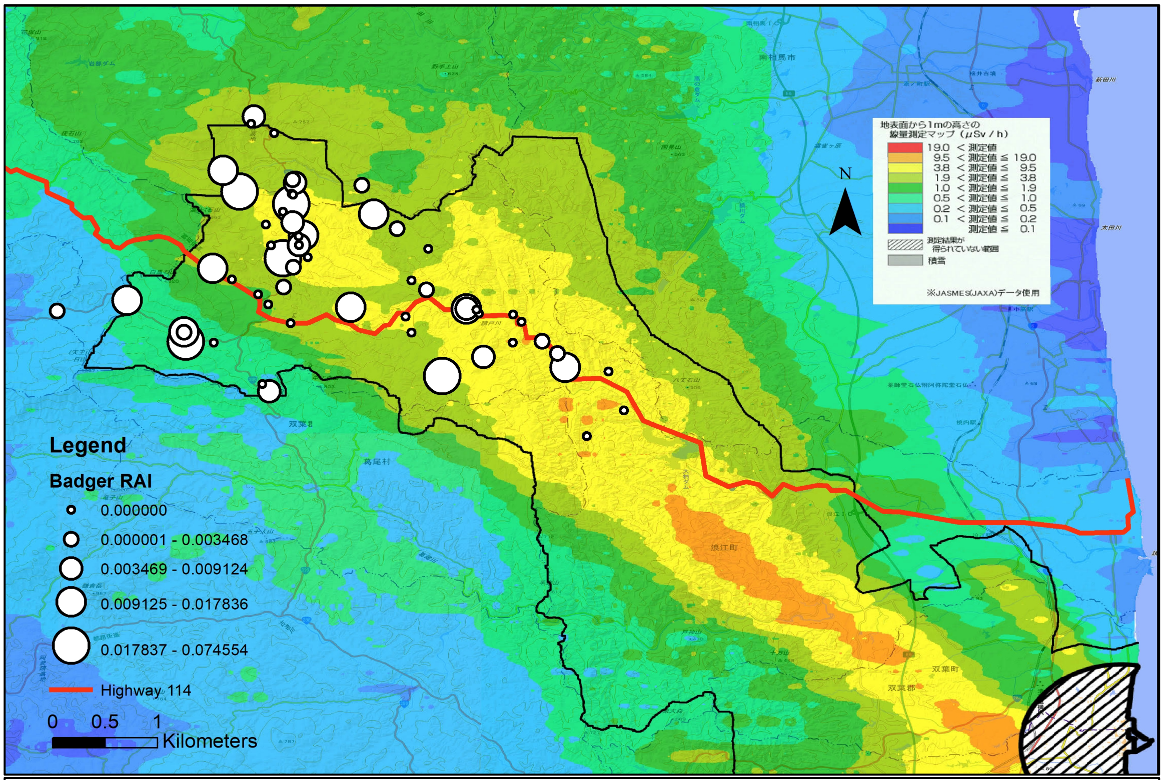
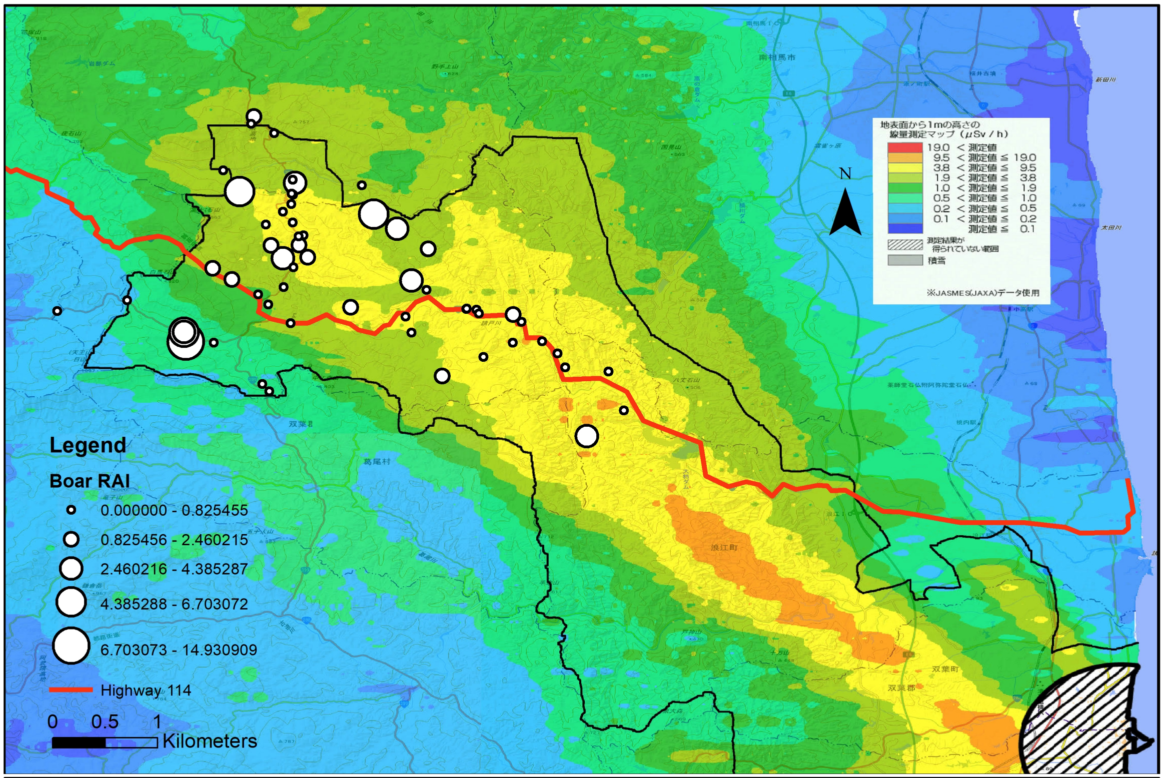


Figure 1.5 Photos from cameras



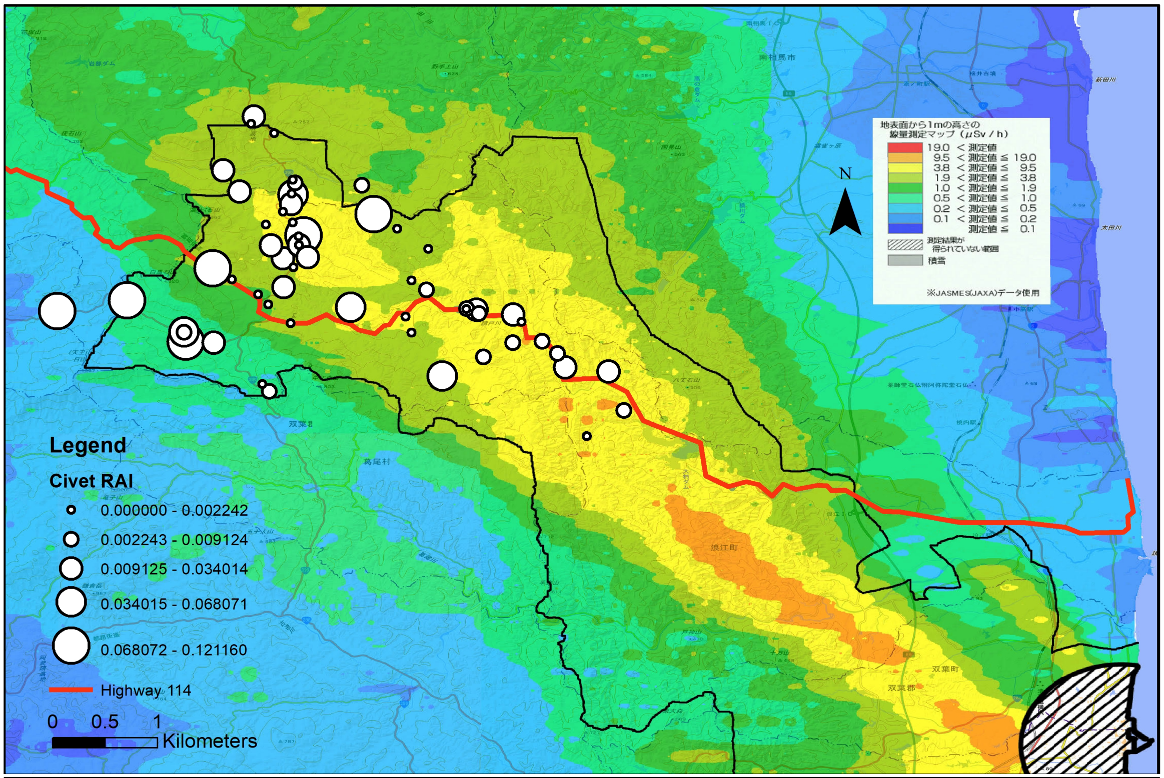
Source	LogWorth	PValue
Ground_Average	12.963	0.00000
NDVI_1	8.870	0.00000
Year	7.782	0.00000
Elevation	6.699	0.00000
ExcZone	4.457	0.00003
Distance_Closest_Water	3.180	0.00066
Lat	2.736	0.00183
Midstory_Average	2.707	0.00197
Distance_Edge	2.642	0.00228
Distance_Highway114	1.981	0.01046
Canopy_Average	1.671	0.02131
Rad_Average	1.641	0.02284
Long	0.864	0.13670

Figure 1.6 Map of RAI and Results of GLM for *M. anakuma*



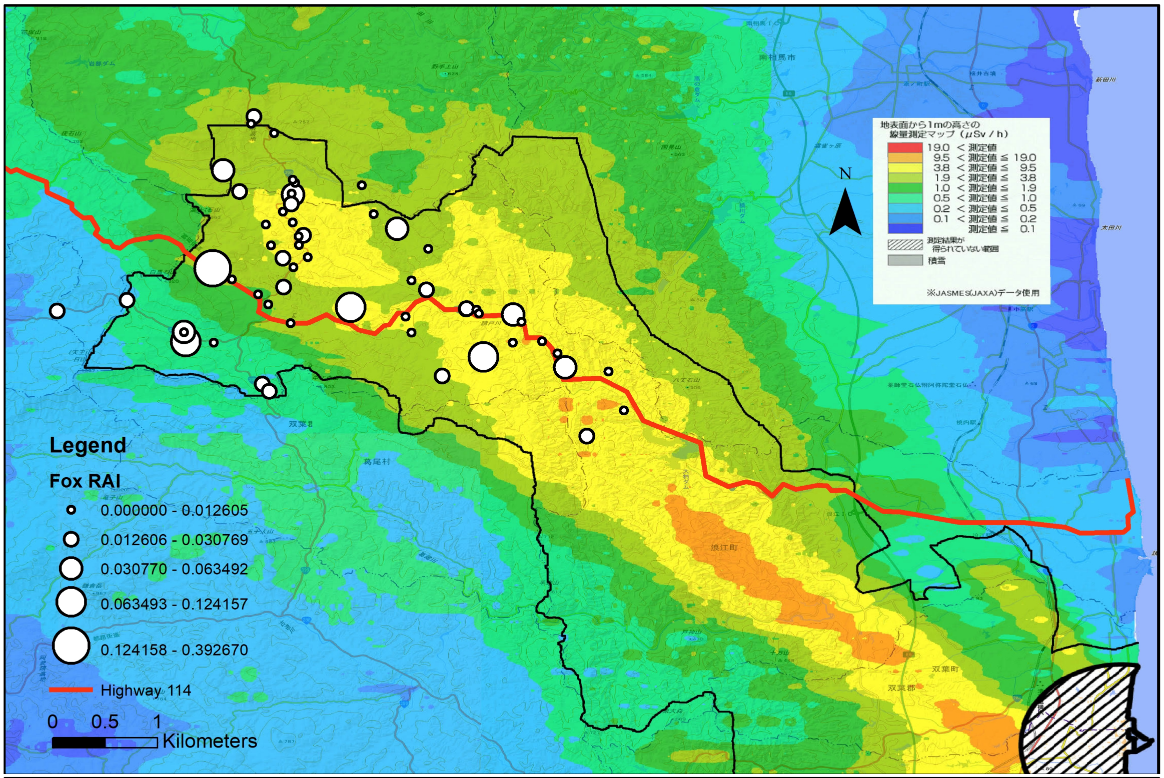
Source	LogWorth	PValue
NDVI_1	48.846	0.00000
Distance_Edge	48.627	0.00000
ExcZone	32.898	0.00000
Year	31.430	0.00000
Long	13.289	0.00000
Distance_Closest_Water	7.143	0.00000
Rad_Average	5.851	0.00000
Distance_Highway114	2.188	0.00648
Midstory_Average	1.929	0.01179
Lat	1.646	0.02262
Canopy_Average	0.464	0.34360
Elevation	0.408	0.39057
Ground_Average	0.268	0.53958

Figure 1.7 Map of RAI and Results of GLM for *S. scrofa*



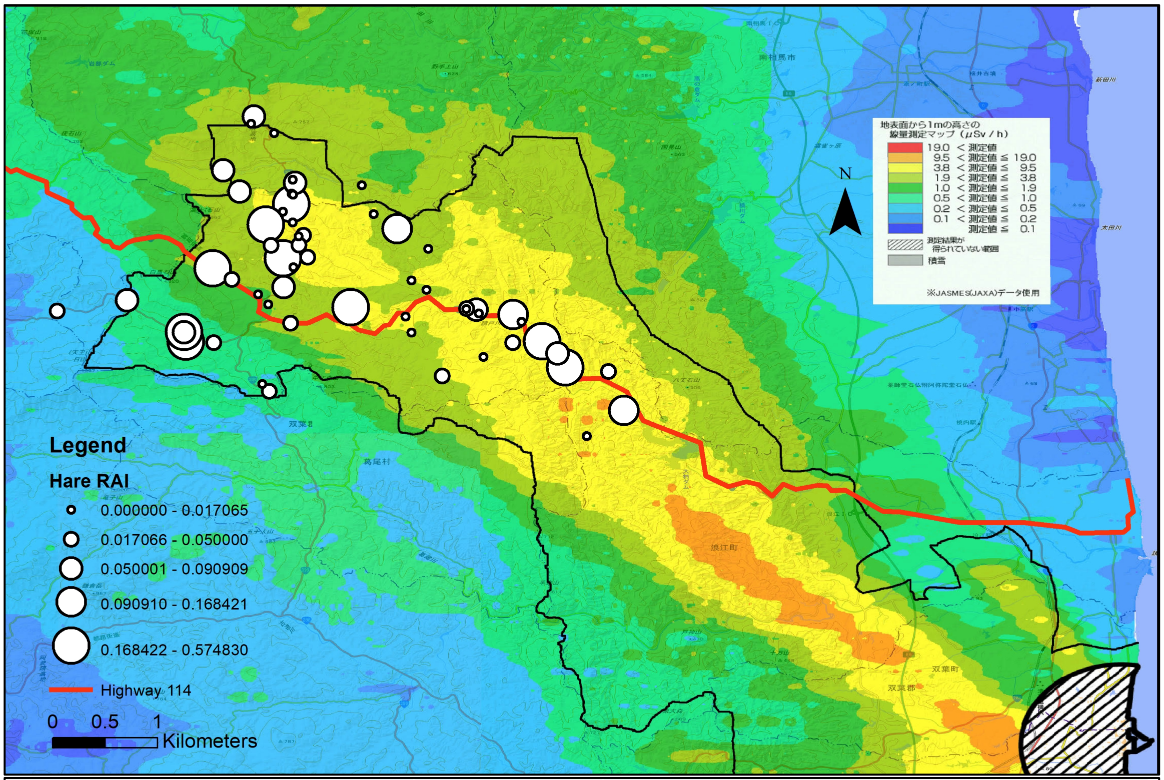
Source	LogWorth	PValue
Long	9.564	0.00000
Canopy_Average	9.548	0.00000
Lat	8.651	0.00000
Distance_Edge	6.726	0.00000
Distance_Closest_Water	4.157	0.00007
Rad_Average	3.721	0.00019
Ground_Average	3.040	0.00091
Year	1.358	0.04381
Elevation	0.895	0.12737
ExcZone	0.405	0.39384
NDVI_1	0.341	0.45621
Midstory_Average	0.242	0.57345
Distance_Highway114	0.121	0.75727

Figure 1.8 Map of RAI and Results of GLM for *P. lavata*



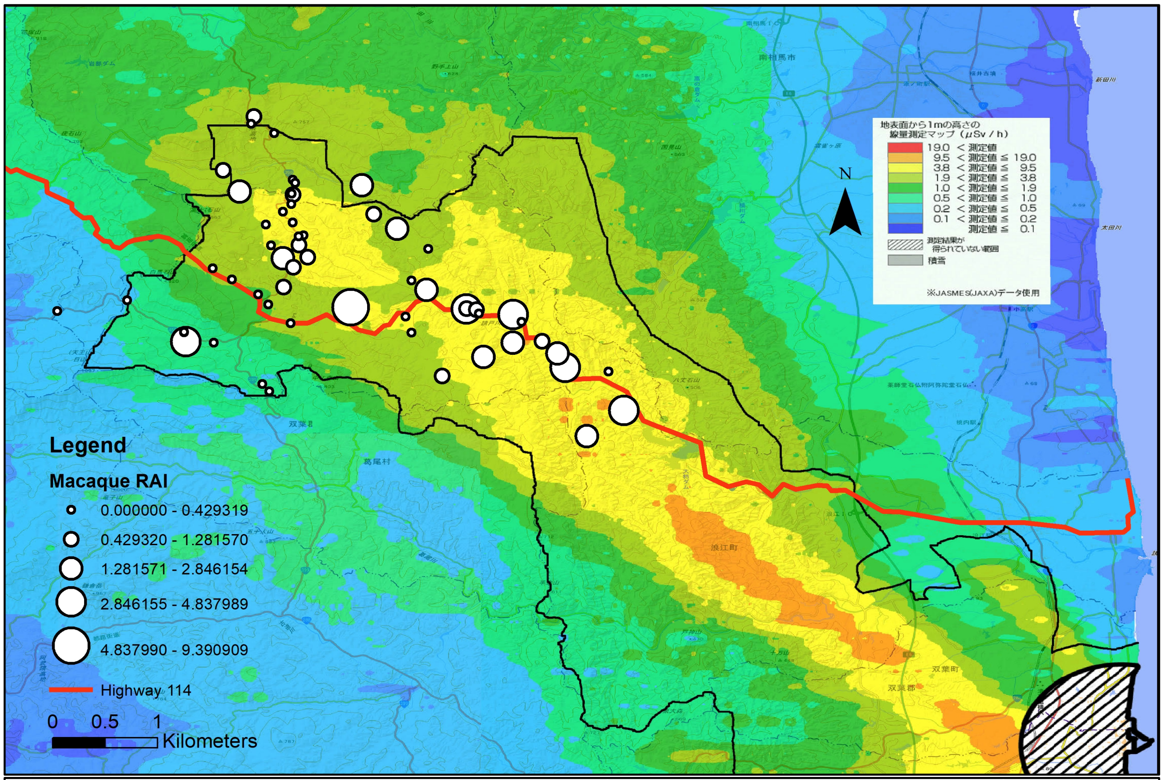
Source	LogWorth	PValue
Distance_Highway114	17.243	0.00000
Midstory_Average	8.849	0.00000
Canopy_Average	7.890	0.00000
Year	4.071	0.00008
Ground_Average	3.985	0.00010
Distance_Edge	3.096	0.00080
NDVI_1	2.756	0.00175
Long	2.388	0.00410
Rad_Average	1.800	0.01584
Lat	1.415	0.03847
Elevation	1.186	0.06514
Distance_Closest_Water	0.703	0.19810
ExcZone	0.661	0.21844

Figure 1.9 Map of RAI and Results of GLM for *V. vulpes*



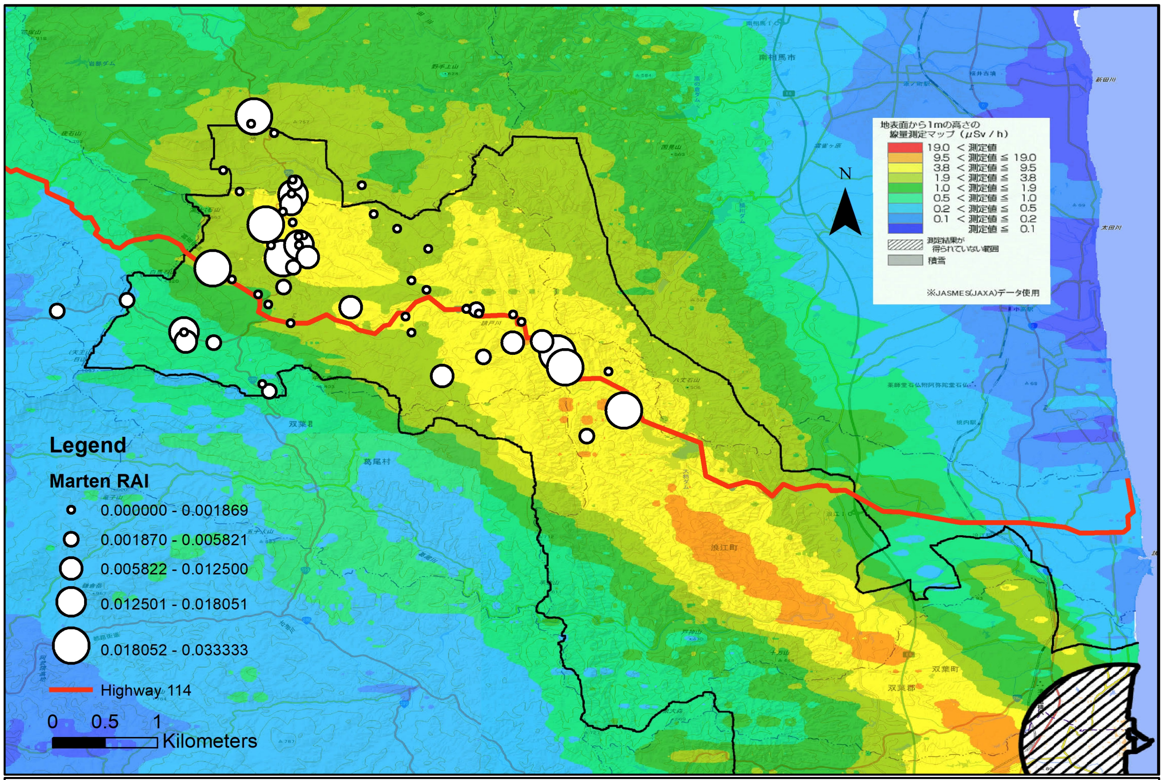
Source	LogWorth	PValue
Distance_Highway114	27.918	0.00000
Year	25.912	0.00000
Midstory_Average	14.865	0.00000
Elevation	12.946	0.00000
Canopy_Average	9.073	0.00000
Ground_Average	4.240	0.00006
Long	1.792	0.01615
Rad_Average	1.761	0.01734
NDVI_1	1.760	0.01736
Lat	0.629	0.23511
Distance_Edge	0.625	0.23704
Distance_Closest_Water	0.382	0.41543
ExcZone	0.271	0.53545

Figure 1.10 Map of RAI and Results of GLM for *L. brachyurus*



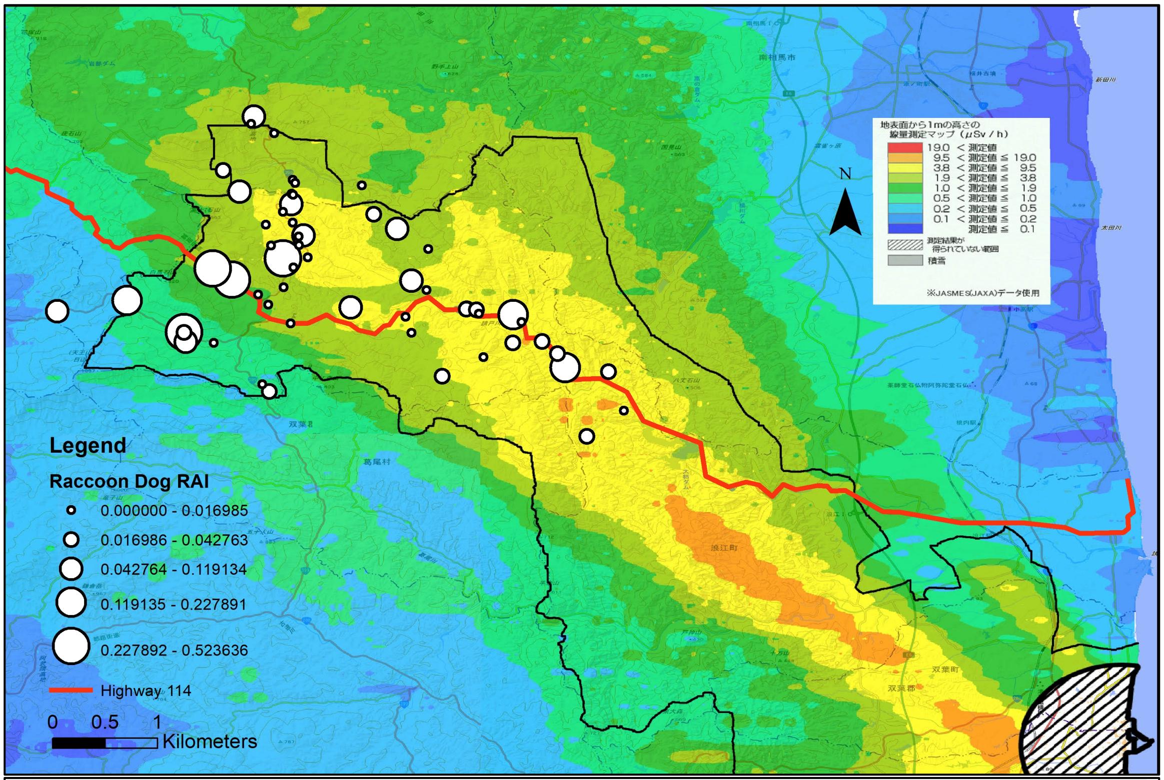
Source	LogWorth	PValue
Long	63.979	0.00000
Distance_Edge	19.554	0.00000
Canopy_Average	11.962	0.00000
Midstory_Average	9.131	0.00000
ExcZone	9.121	0.00000
Elevation	6.562	0.00000
Lat	6.417	0.00000
Distance_Closest_Water	2.103	0.00789
Rad_Average	2.088	0.00816
NDVI_1	1.505	0.03130
Year	1.414	0.03858
Distance_Highway114	0.514	0.30650
Ground_Average	0.297	0.50506

Figure 1.11 Map of RAI and Results of GLM for *M. fuscata*



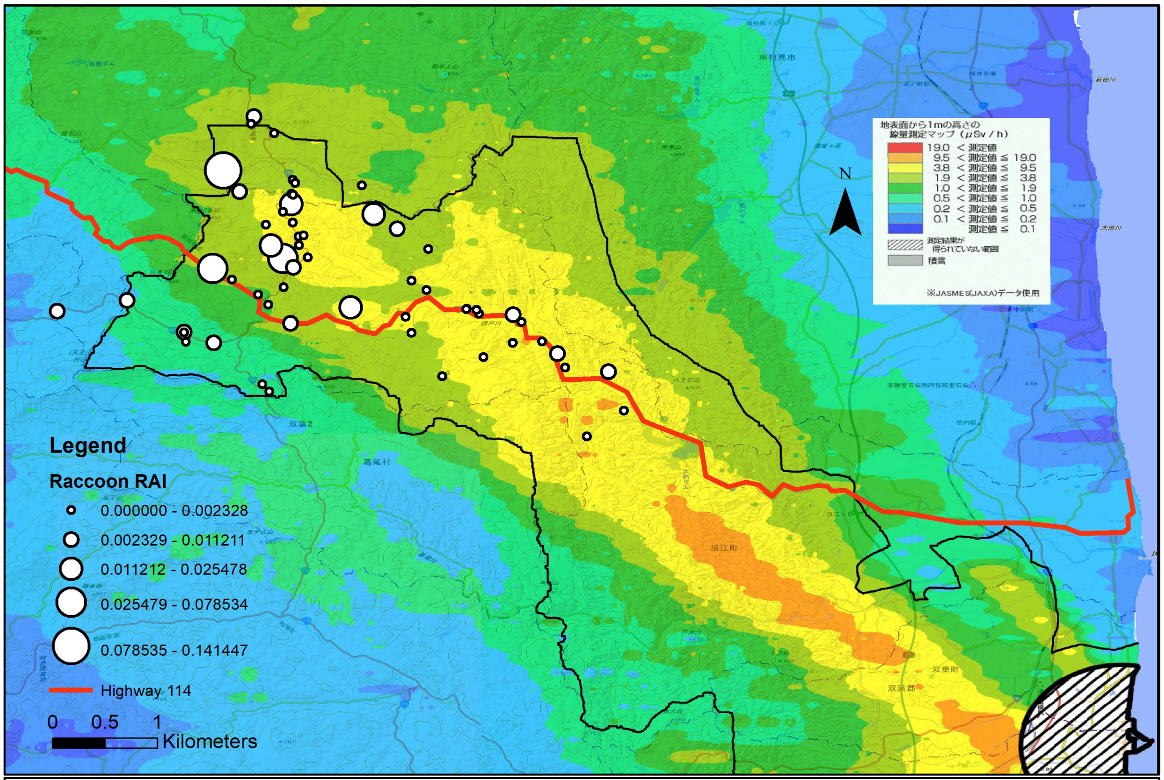
Source	LogWorth	PValue
Year	8.877	0.00000
Long	8.675	0.00000
ExcZone	7.403	0.00000
Lat	5.873	0.00000
Elevation	5.824	0.00000
Canopy_Average	4.767	0.00002
Distance_Closest_Water	2.075	0.00842
Distance_Edge	0.627	0.23584
Rad_Average	0.423	0.37748
Distance_Highway114	0.310	0.48954
Ground_Average	0.181	0.65954
Midstory_Average	0.080	0.83169
NDVI_1	0.070	0.85095

Figure 1.12 Map of RAI and Results of GLM for *M. melampus*



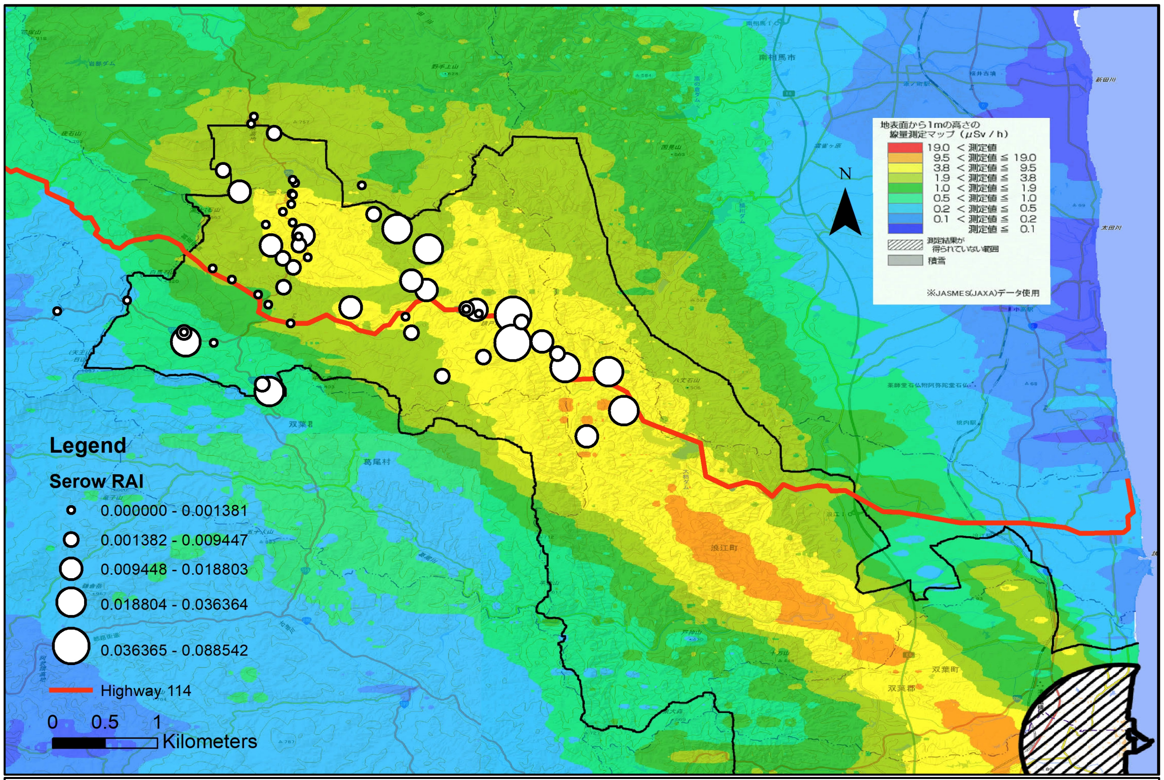
Source	LogWorth	PValue
Elevation	15.961	0.00000
Midstory_Average	11.160	0.00000
Lat	9.919	0.00000
Rad_Average	7.770	0.00000
Year	7.214	0.00000
NDVI_1	6.962	0.00000
Long	3.790	0.00016
Distance_Highway114	2.144	0.00717
Ground_Average	1.406	0.03926
Canopy_Average	0.852	0.14055
Distance_Closest_Water	0.546	0.28422
ExcZone	0.263	0.54558
Distance_Edge	0.236	0.58071

Figure 1.13 Map of RAI and Results of GLM for *N. procyonoides*



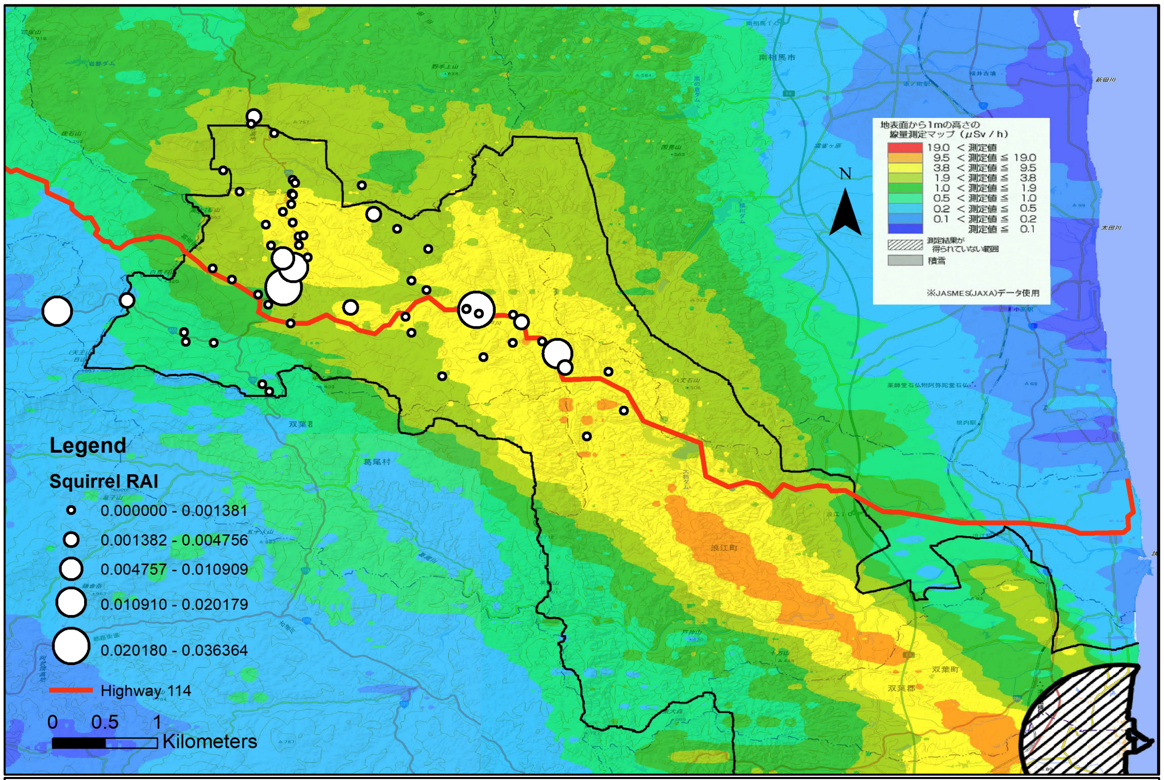
Source	LogWorth	PValue
Distance_Highway114	9.465	0.00000
Midstory_Average	4.568	0.00003
Lat	3.366	0.00043
Distance_Edge	3.043	0.00090
Distance_Closest_Water	1.230	0.05889
Ground_Average	1.189	0.06476
Rad_Average	0.588	0.25833
Elevation	0.480	0.33147
ExcZone	0.312	0.48804
Year	0.310	0.48991
Long	0.255	0.55566
NDVI_1	0.144	0.71842
Canopy_Average	0.129	0.74337

Figure 1.14 Map of RAI and Results of GLM for *P. lotor*



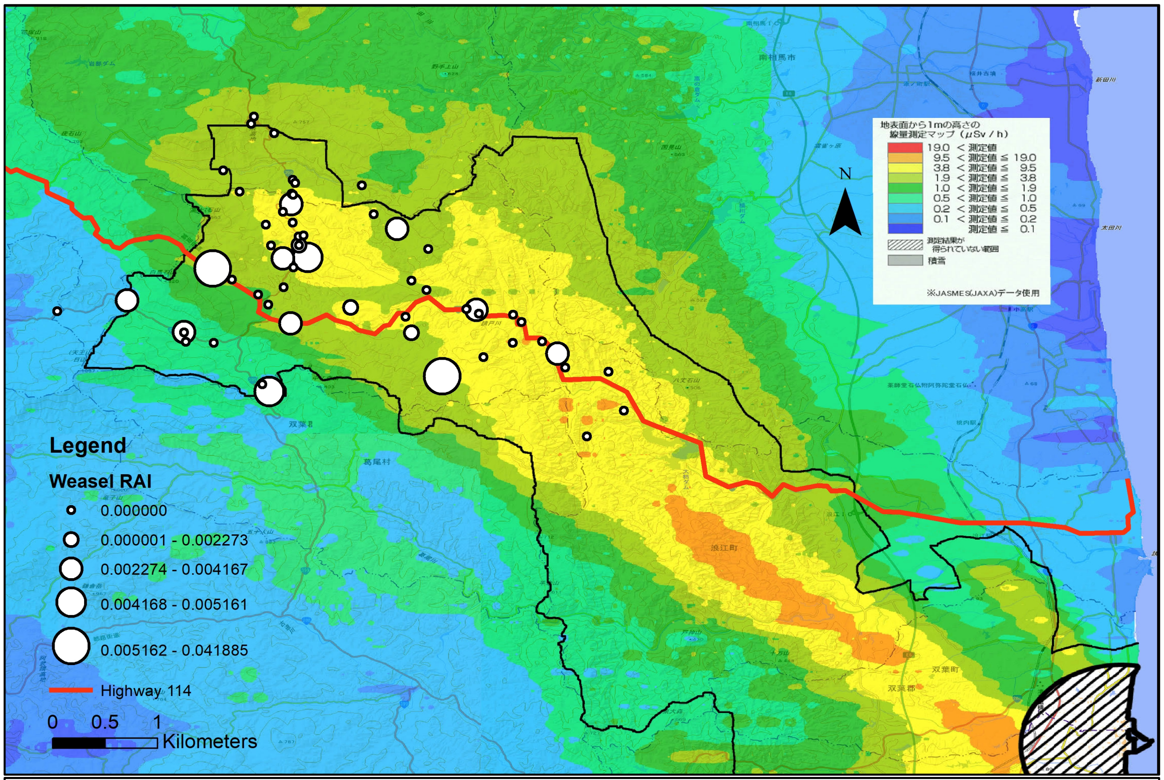
Source	LogWorth	PValue
Midstory_Average	13.622	0.00000
Year	9.402	0.00000
ExcZone	8.710	0.00000
Long	7.176	0.00000
Distance_Highway114	6.653	0.00000
Distance_Edge	3.648	0.00022
Lat	2.901	0.00126
Elevation	1.449	0.03556
NDVI_1	1.160	0.06923
Distance_Closest_Water	0.819	0.15175
Ground_Average	0.625	0.23687
Canopy_Average	0.293	0.50941
Rad_Average	0.059	0.87321

Figure 1.15 Map of RAI and Results of GLM for *C. crispus*



Source	LogWorth	PValue
Distance_Closest_Water	17.821	0.00000
Midstory_Average	9.723	0.00000
Lat	8.041	0.00000
Distance_Edge	6.194	0.00000
ExcZone	5.071	0.00001
Year	4.555	0.00003
Ground_Average	2.129	0.00744
Canopy_Average	2.064	0.00862
Long	0.211	0.61460
NDVI_1	0.124	0.75095
Elevation	0.067	0.85695
Distance_Highway114	0.025	0.94465
Rad_Average	0.004	0.99145

Figure 1.16 Map of RAI and Results of GLM for *S. lis*



Source	LogWorth	PValue
Year	5.013	0.00001
Distance_Edge	4.418	0.00004
ExcZone	4.328	0.00005
Distance_Highway114	3.863	0.00014
Ground_Average	3.749	0.00018
Elevation	3.482	0.00033
Midstory_Average	2.382	0.00415
Lat	1.555	0.02788
Rad_Average	1.507	0.03114
NDVI_1	0.972	0.10660
Long	0.772	0.16904
Distance_Closest_Water	0.660	0.21857
Canopy_Average	0.171	0.67481

Figure 1.17 Map of RAI and Results of GLM for *Mustela spp*.

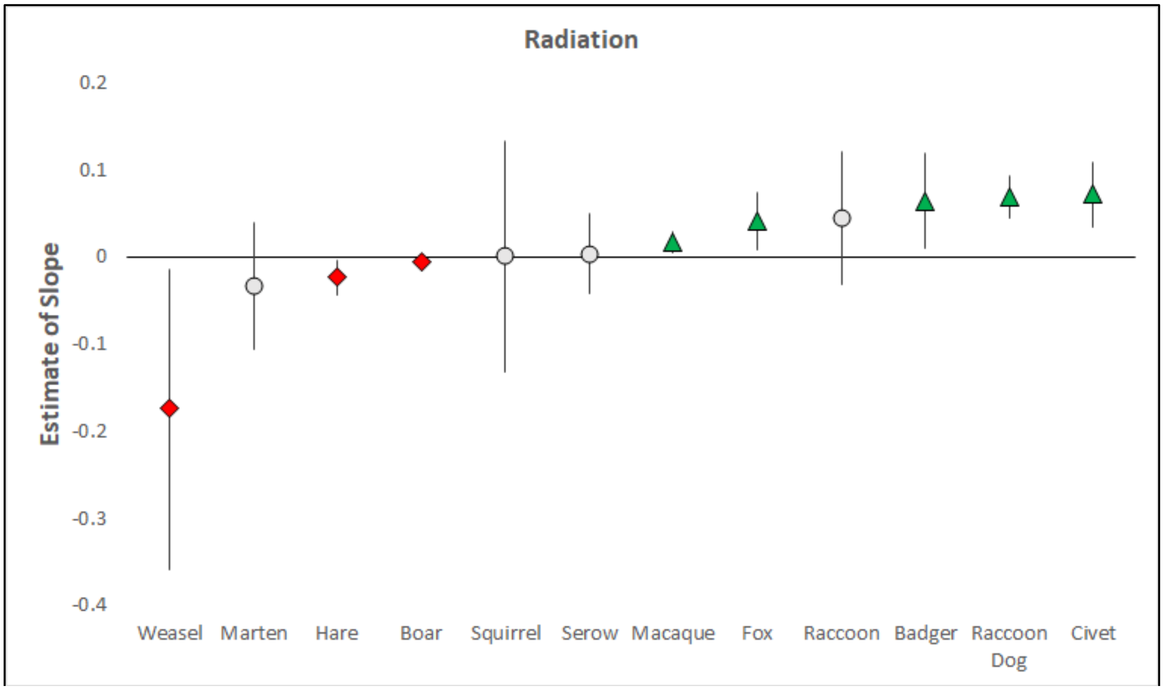


Figure 1.18 Estimate of slopes for the relationship between RAI and average ambient radiation levels

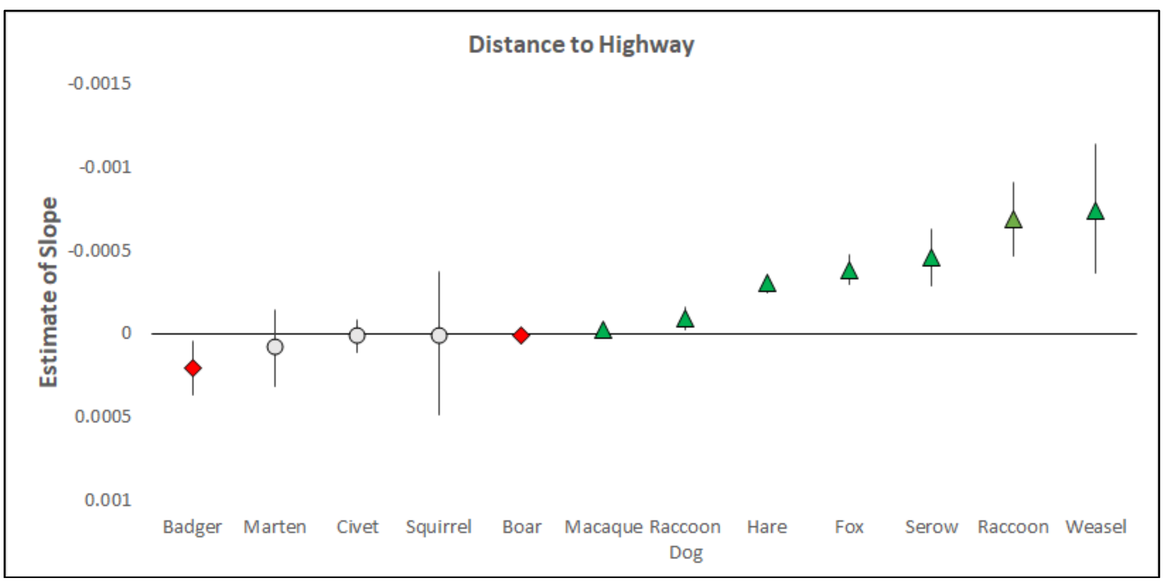


Figure 1.19 Estimate of slopes for the relationship between RAI and the distance to Highway 114

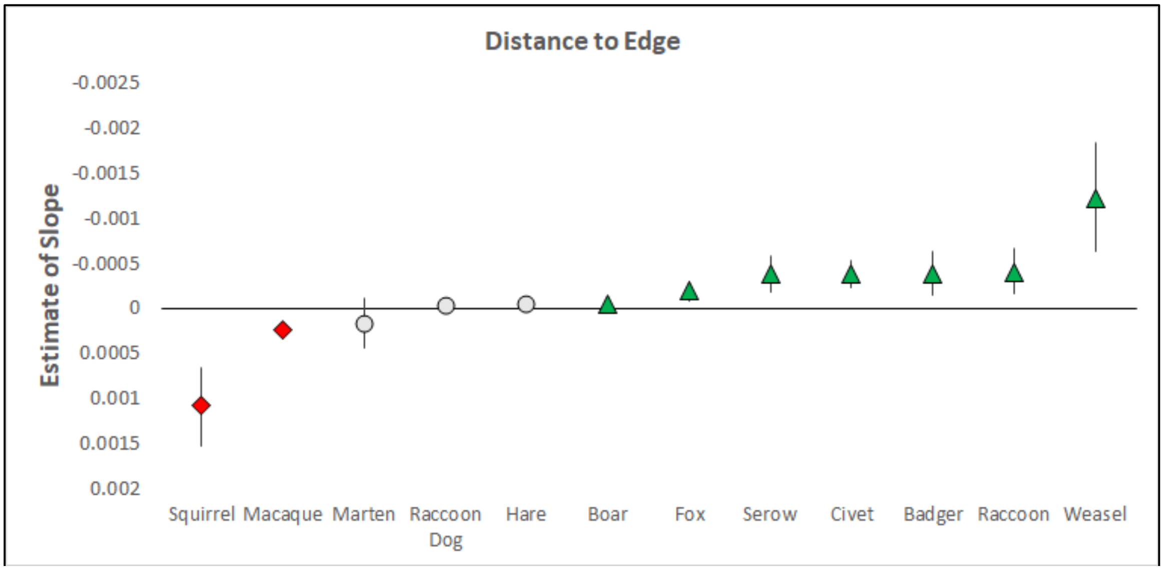


Figure 1.20 Estimate of slopes for the relationship between RAI and the distance to the edge of the exclusion zone

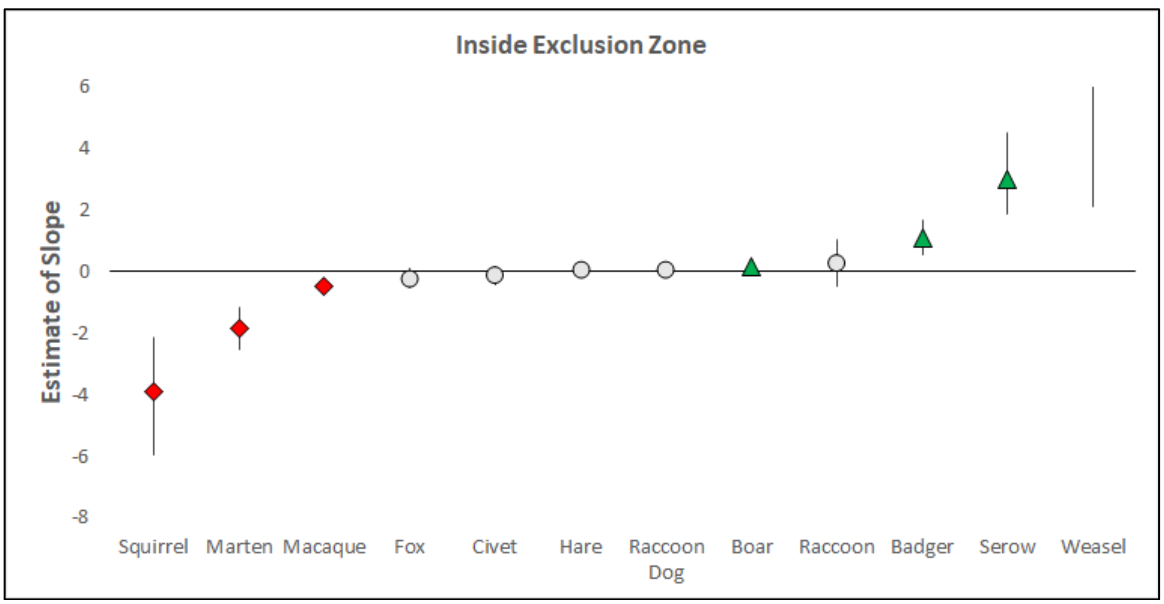


Figure 1.21 Estimate of slopes for the relationship between RAI and if a camera was inside or outside of the exclusion zone

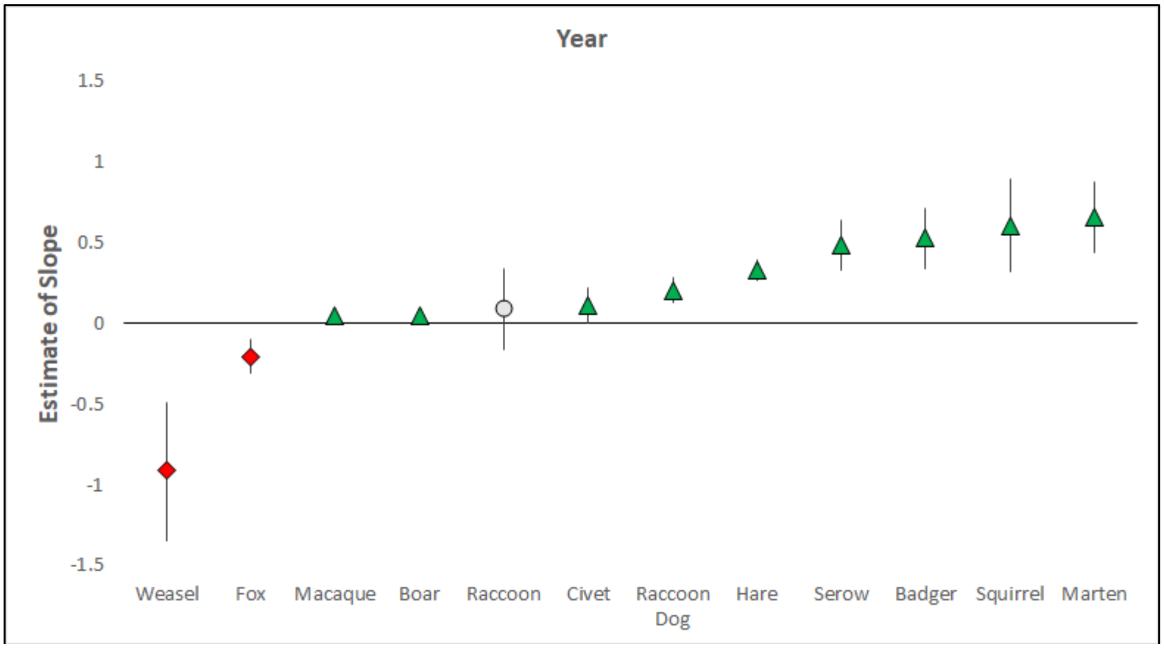


Figure 1.22 Estimate of slopes for the relationship between RAI and year

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